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LANDFORMS, SOILS WITH FRAGIPANS, AND FOREST ON A SLOPE IN THE HARVARD FOREST

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W. H. Lyford, J. C. Goodlett, and W. H. Coates[1]

ABSTRACT

This study was made on an 8-acre slope toward the base of a large drumloidal hill. Firm, dense till underlies most of the study area. A small part of the area is underlain by glaciofluvial sand and gravel, mostly covered by colluvium derived from the till upslope. The soils derived both from the dense till and from the colluvium over the sand and gravel deposits contain a hard, brittle horizon, the fragipan. This fragipan horizon probably formed shortly after the deposition of the drift and the formation of the colluvium. Since formation of the fragipan, mass movements of the upper 3 or 4 feet of the soil materials overlying the fragipan have resulted in landslides and local accumulation of stones and boulders. The distribution and orientation of large boulders also indicates large-scale gravity movement upon the surface of the fragipan.

The Brown Podzolic soils on the complex slopes produced by landsliding, as well as the soils in which the large boulders are embedded, are identical to the soils in the more stable parts of the area. Soils range in internal drainage from somewhat excessively to very poorly drained.

The soils support an old-growth forest of rather uniform composition. Although 19 different species of trees are present in the crown canopy, 7 species (red maple, white pine, red oak, black birch, paper birch, white ash, and sugar maple) constitute most of the stand. Of these species only the distribution of the white pine and white ash is related to variations in the soils. White pine is concentrated in a small area where sand and gravel deposits reach the surface and a fragipan is lacking; white ash is in an area along a small intermittent stream where the soil stays wet for long periods.

This study indicates that presence or absence of fragipan is of great significance in mapping forested soils. It also indicates that where a fragipan occurs differences in degree of natural soil drainage are not paralleled closely by differences in forest composition.

[1] Position at time of study respectively: Senior Soil Correlator, Soil Conservation Service; Forest Geographer, Harvard Forest: and State Soil Scientist, Soil Conservation Service.

INTRODUCTION

This report relates the findings of a coordinated study of landforms, soil and forest in a small area within the Harvard Forest, in north central Massachusetts. The study is a product of an informal collaboration between the U. S. Department of Agriculture and the Harvard Forest that began more than twenty years ago. During this period, the general problem of developing soil map units that would possess maximum usefulness in forested areas has been attacked from several points of view (Goodlett, 1960).

For more than forty years the Harvard Forest has been involved in soils problems, and to an ever increasing extent. At the onset of forest management in 1908, most of the merchantable timber within the Harvard Forest consisted of white pine.[1] Most of the pine had originated on cleared land that had been farmed early in the nineteenth century. The policy adopted by the Harvard Forest staff visualized a financially self-supporting, sustained-yield system of management, based largely upon the harvest and natural regeneration of white pine. The problems of seeding and seed germination in the cutover pine stands were readily solved. However, young hardwoods of seedling and sprout origin, present in the young stands, overtopped and threatened to kill the young pine seedlings within three years after cutting. By 1918, it was recognized that these difficulties with the hardwoods were less severe on the sand plains of glaciofluvial origin than on the till-covered uplands (Fisher, 1918). This differential was reflected in the frequency and intensity of control measures recommended for the two kinds of sites. By 1925, the upland till soils had been divided into two categories, which reflected conditions in the young stands (Cline and Lockard, 1925). On the "medium soils," pine regeneration appeared possible of attainment in mixture with hardwoods, but on the "heavy soils," pure hardwood stands resulted from the cutting of pine. Recognition of the two categories depended upon the rather general criteria of topographic position and texture of the surface horizons. A modification of this classification was used in an extensive study of the hardwood stands that had followed the cutting of old-field white pine (McKinnon, Hyde, and Cline, 1935). This study showed that the species composition as well as the quality and volume of the stands was related to the soil categories.

[1] See Table 2 for scientific names of species mentioned in the text.

In 1927, a soil survey of Worcester County, Massachusetts (Latimer, Martin, and Lanphear, 1927), became available for use at the Harvard Forest.

In June 1939, a conference of soil scientists and foresters was held at the Harvard Forest to discuss the problem of soils mapping in forested areas. No recommendations for changes in soil survey methods were adopted by the conference, but the conference concluded that detailed soils maps of several experimental forests would be desirable. Beginning in 1939, the soils within the Harvard Forest were mapped at a scale of 200 feet to the inch by C. S. Simmons, of the U.S. Department of Agriculture (Simmons, 1939–41).

Lutz and Cline (1947), Spurr (1950, 1956), and Stout (1952) provided valuable information concerning the usefulness of the experimental soils maps. All believed that soil variation strongly affected forest composition. All were concerned with species composition as related to soil variation, not with differences in production rates in stands of similar composition. All encountered difficulty in correlating stand composition with the mapped soil units in the well-to excessively-drained till soils, which occupy most of the area. Lutz and Cline and, particularly, Spurr, believed that simple rearrangements of the mapped soil types into modified drainage classes yielded useful correlations with stand composition. On the other hand, Stout showed that the boundaries of the soil map units in areas of well-drained till soils were unrelated to species composition and forest type boundaries in the stands examined by him.

All pointed out the importance of soil characteristics that affected moisture regimes, and the need for a refinement of soil-drainage classes. All believed that an unnecessary number of soil series had been mapped. This was reflected in the grouping of series in the modified drainage classes. However, the need for distinguishing between soils on till and stratified drift was recognized by all, and particularly emphasized by Spurr (1950). Perhaps most important from the point of view of improving the value of soil map units for forested land was Stout's demonstration of the effect of firm layers on species distribution. His deep pits also emphasized the shortcomings of the soil auger as a tool for examining soil materials.

The results of previous studies suggested that surficial deposits containing firm layers generally supported hardwood stands containing large proportions of red oak and white ash trees, and that this kind of deposit characterized localities where attempts to regenerate white pine stands had failed. Surficial deposits lacking firm layers generally supported hardwood stands containing large proportions of white and black oak trees, or mixed stands of pine and oak trees. Furthermore, a reexamination of soils in some of the localities where attempts to regenerate white pine stands had succeeded revealed till without firm layers. Thus, presence or absence of firm layers in soils derived from till appeared to coincide with pronounced differences in composition of hardwood stands and, even more strikingly, with success or failure of the long-term experiments in the regeneration of pure stands of white pine.

In July 1954, G. D. Smith, W. H. Lyford, and W. H. Coates, of the Soil Conservation Service, U. S. Department of Agriculture, met with the Harvard Forest staff to consider ways of exploiting the knowledge gained from experience with the detailed soils maps and the subsequent studies of the soil materials. It was decided to study in detail and re-map small areas in the Forest in these two kinds of till soils. As a beginning, a small area where the surficial deposits generally contained a firm layer was chosen. This report relates the results of that study.

For 2-week periods in the fall of 1955, 1956, and 1957, detailed studies were made in an 8.4-acre area within Compartment I of the Tom Swamp Tract. This area had never been cleared for agricultural use and supported a stand of mature trees. The soils in the area had been mapped by Simmons in 1939 as Charlton stony loam.

Hatheway (1954) studied the relations between the surficial deposits, soil moisture regimes, and the vegetation in this 8-acre area. In making this study, pits were dug and their location plotted on a large-scale topographic map (66 feet to the inch, contour interval 3 feet). Periodic measurements of standing water in the pits showed wide variations in levels and duration of the temporary water tables. These variations in water tables were related in a general way to variations in density of the subsoils. Thus, areas lacking firm layers did not have perched, temporary water tables; and areas underlain by firm layers usually showed temporary water tables the level of which in the soils often could be related to the position of the firm layer in the profile. Local distribution of tree species was related to water table regimes and thus, in turn, to variations in subsoil density. Hatheway believed that at least two soil series should be recognized within the area.

Hatheway's topographic map, the mapped soil pits, and the water table data offered an excellent starting point for detailed soil and vegetation studies. These joint studies had four general aims: 1) to examine the minor topographic features of the area, interpret their origin, and determine their relation to soil variation and soil development; 2) to study the distribution of stones and boulders and the origin of their distribution patterns; 3) to examine and re-map the soil variation and, with particular attention to the firm layers, interpret the origin of these variations; and 4) to study independently the variation within the forest stand, and to search for relations between stand variations, topographic form, and variations in the soils. By this means, an evaluation of soils map units in terms of the forest vegetation could be obtained contemporaneously with the preparation of the soils map.

GENERAL DESCRIPTION OF THE AREA

This study was made on the northwest side of a large drumloidal hill in Compartment I of the Tom Swamp Tract mostly within a rectangular area of 8.4 acres (Fig. 1).

Two major kinds of surficial deposits characterize Tom Swamp I. Thick gravelly fine sandy loam till covers about 90 percent of the area. This is derived from granite and schist and is like that on most drumlins or drumloidal hills in New England where granite or schist predominates. Thickness of the till over most of the area is thought to exceed 6 to 10 feet. No bedrock is exposed.

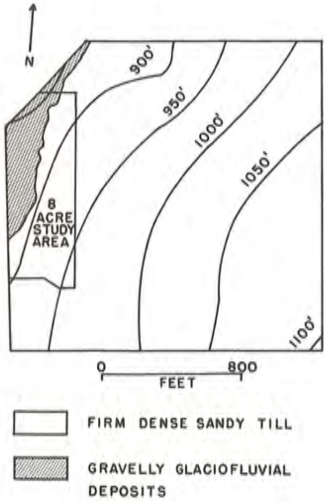
At the base of the slope is a glaciofluvial or water-sorted till deposit. Most of this area is mantled by 2 to 3 feet of stony, bouldery colluvium derived from the till-covered slope just above. In places the water-sorted material is covered by a silty mantle apparently of aeolian origin. In a few places, the water-sorted material is exposed at the surface.

The upper part of Compartment I has a long, smooth 10 percent slope. Toward the base the slope steepens and is interrupted abruptly in a few places by short, steep slopes that have a tendency for parallel arrangement. These are shown in Figure 2. The largest of the parallel slope sequences covers about 2 acres in the 8-acre detailed study area.

All of Compartment I is stony and bouldery. In general, boulders are fairly uniformly distributed on the smooth slope in the upper part of the Compartment but form boulder fields and boulder streams toward the base of the slope. Areas that have been cleared and used for crops are relatively stone-free.

Well-drained Charlton and Paxton soils and moderately well-drained Woodbridge soils that are derived from till cover most of the Compartment. These are members of the Brown Podzolic great soil group and are extensive and important soils in New England. When cleared of forest and surface stone they are among the most productive agricultural soils in the northeastern United States.

A conspicuous feature of the soils derived from the till is the fragipan, a compact, hard, dense, brittle layer that is encountered at depths of 20 to 30 inches below the surface of the soil and continues to depths of 4 to 5 feet. It lies over a firm massive till but is harder and more brittle than the till below.



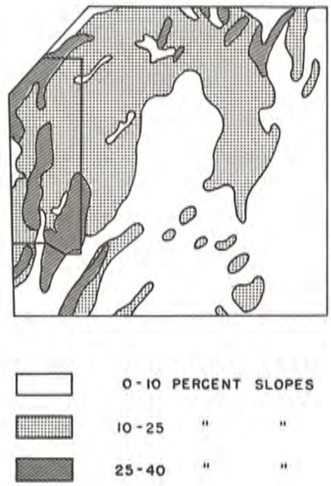
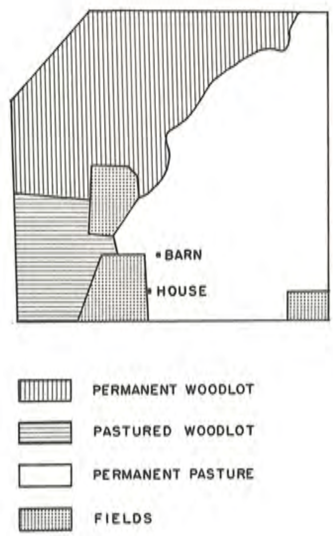


FIGURE 1. (UPPER LEFT) — Contours, surficial deposits, and location of 8 acre study area in Compartment I, Tom Swamp tract, Harvard Forest. Contours are from U.S.G.S. Petersham, 7½ minute quadrangle, 1946.

FIGURE 2. (UPPER RIGHT) — Location of slopes, classed by percent gradient, in Tom Swamp I.

FIGURE 3. (LOWER RIGHT) — Probable land use on the Tom Swamp tract about 1830.



Present vegetation is principally transition hardwoods with a large component of red oak, paper birch, red maple, and white pine in the overstory. In 1907, when the tract was given to Harvard University, the upper half of the Compartment was nearly pure white pine.

The pre-settlement forest in the northwestern part of the area consisted of hardwoods. This is known from historical evidence (Raup and Carlson, 1941). Studies of the existing trees, of stumps, and of other ground features indicate that this portion of the Compartment has always been in forest. All of the area has been pastured, but only the area once occupied by pure white pine was a permanent pasture. Figure 3 shows how the land was used about 1830 when farming in this section of the state was at its peak.

CHARACTERISTICS AND ORIGINS OF LANDFORMS

At the beginning of the detailed study of the 8-acre tract, a reconnaissance was made to become familiar with the landforms, soils, and forest cover. This showed that no simple relationship of soils and forest existed in this area of intermingled short steep slopes, boulder concentrations, and various degrees of soil wetness. Consequently, the landscape as a whole was studied. The characteristics and origins of landforms, including the origin of boulder concentrations, were studied in addition to the soils and vegetation.

Long smooth slopes

Slopes in almost half of Compartment I range in gradient from 0 to 10 percent with more than three quarters of the area having slopes of less than 25 percent (Fig. 2). Long smooth slopes such as these characterize the drumlins or drumloidal hills throughout southern New England, as well as many of the lower slopes of northern New England.

The gentle upper slopes in the southeastern part of the area are interrupted in a few places by small knolls or lobate terrace-like ridges and there are a few small depressions.

The knolls and ridges trend generally southwest-northeast, parallel to the contours, and their long axes range from 100 to 500 feet in length. Local relief generally is 10 to 15 feet. The longer ridges are slightly convex downslope in plan view, and are adjacent to the steeper slopes. The sides of these ridges and knolls tend to be steeper on the downhill slopes. Springs and seeps are found at the base of the downhill sides of the ridges and knolls.

The small depressions are less than a quarter acre in area and have a maximum depth of 5 feet. The depressions are ponded during the wetter parts of the year and remain wet for a longer time than the surrounding soils. However, all of them have mineral soils. Several other small areas on the slope are saturated during wet seasons of the year. They are not closed depressions, however, and are never ponded.

At the upper part of the long smooth slope, the soils are well or moderately well drained. Water tables during the growing season generally are more than 20 inches beneath the ground surface. When the leaves are not on the trees the water tables may be at 14 or 18 inches for fairly long periods. At the lower part of the slope, the soils are somewhat wetter. Here water tables during the growing season are at 14 to 18 inches for fairly long periods, and in fall and winter they are only 6 to 12 inches from the surface. In very wet periods during the growing season these soils are saturated for several days.

A few small but definite stream channels are cut into the long smooth slope, but these are dry most of the time. Most of them are strewn with boulders.

Although the origin of the drumlin or drumloidal hill upon which Compartment I is located is beyond the scope of the study, a general summary of opinion as to characteristics may be helpful. Presumably, the dense basal till that constitutes the bulk of a drumlin was deposited under the glacier, and its inverted spoon-bowl form was molded by the ice. In some drumlins, an upper mantle is distinguished from the underlying basal till by means of coarser texture, greater stone content, or differences in lithology or shape of stones. This upper mantle, or superglacial till, presumably was derived from rock fragments that were carried in or on the ice and let down on the basal till when the ice melted.

A freshly exposed drumlin would be subject to erosion by running water and the resulting formation of stream channels, as well as truncation of its slopes by ice-marginal streams. Climatic conditions prevailing in an area adjacent to an ice sheet might result in deposition of wind-blown silts and fine sands over its surface, and intense frost activity might accelerate gravity movements of the mantle. All these processes would affect and be affected by the restoration of a plant cover.

In Compartment I, the upper parts of the surficial deposits show a looser consistence and a somewhat higher proportion of coarse skeleton than the underlying materials. As will be demonstrated later, these features are most readily explained as the result of pedogenic processes acting upon a uniform deposit.

In one or two places at the base of the slope in Compartment I, deep pockets of silt up to several feet in diameter can be seen. The silt pockets may represent remnants of an aeolian deposit. However, no slit deposits have been found on the long smooth upper slope. Neither is the solum any more silty than the underlying till. Stout (1952) concluded that the present soil solum was derived in part from wind-blow silt and fine sand deposited on the surface of the till. Subsequent mixing with the sandy till produced a surface layer of "loam." This loam was thought to be much finer in texture than the till below. Colby, Light and Bertinuson

(1953) concluded that deposition of aeolian silt was more or less continuous over southern New England, and they believed that the present solum of most soils was derived from material containing quantities of aeolian silt. Tamura et al. (1957) have shown that aeolian silt is common locally along the Connecticut Valley area but disappears at a distance of three or four miles from the source. At present, the soils on the upper slopes provide no conclusive evidence that a distinctive mantle of aeolian material ever existed.

Evidence of mass movement subsequent to formation of the drumloidal hill can be found in Compartment I. Materials to a depth of several feet may have been removed from the slopes and redeposited at the base of the hill. If the base of the slope had been subjected to the action of ice-marginal streams, the materials might have been removed from the area entirely. Downslope movement, whether cataclysmic or particle by particle, might remove any deposits present above the dense till. Under certain conditions, a large amount of material can be moved by frost activity, and slopes once irregular in form can be smoothed (Denny, 1956).

The knolls and ridges on the long slope may be depositional irregularities. In other words, the surface of the original deposit may not have been smooth. Alternatively, the till which makes up the knolls may have been material carried in or on the ice, in which event a discontinuity of some kind would be expected at the base of the deposit. In Compartment I the material comprising the knolls is similar to the material on the surrounding slope. The soils on these two areas are identical even to the presence of a fragipan.

These bulging slopes and knolls may be the result of a local downslope movement of only a few inches or feet. The whole mass may have bulged slightly as any plastic material tends to do when placed on a slight slope. This hypothesis of mass movement is proposed elsewhere in this report to account for the presence of short steep slopes and associated features which occur on the same tract and on these same materials.

The knolls and hollows that interrupt the long smooth slope cause local variations in depths to water tables. In 1960 and 1961, small post hole-size wells were dug at 50-foot intervals down the long smooth slope of Compartment I. The wells revealed that the level of free water during the fall, winter and spring as well as the upper surface of the fragipan has less relief than the surface of the ground. Thus, depths to water and to the fragipan are less in closed depressions and immediately upslope from ridges than in areas of uniform slope, and strikingly less than at the highest point of the ridges. Patric (1956) noted that the vegetation immediately upslope from the low ridges indicated that these places were wetter than the ridges, although the soil profiles were similar. The wetter areas immediately upslope from the low ridges may be the result of downslope mass movement of materials overlying the fragipan to form the ridges. This contention must rest upon general argument from evidence derived from study of similar features in the 8-acre study area. Landsliding would act to bring the fragipan surface nearer to the ground surface and thus raise water levels upslope from the ridges. The closed depressions are immediately downslope from the knolls and ridges. The origin of the depressions, therefore, seems unrelated to the formation of the adjacent knolls and ridges. However, the concave areas indicate that erosion proceeds at a slow rate in this part of Compartment I. Although the soils in the closed depressions are similar to those in adjacent parts of the long slope, detailed study of the sediments might yield information concerning erosion of the slopes, the problem of aeolian deposits and, if the sediments contain pollen, the nature of past vegetation.

One line of evidence suggests that the knolls and ridges on the long smooth slope were formed by mass movements. Upslope from the largest of the low ridges a stone concentration forms an indistinct pattern reminiscent of patterned ground like that described in the Arctic (Washburn, 1956). Rude strings of stones are aligned downslope, but they intersect each other in some places at about the same angle as that of stone-bordered polygons. On the ridge itself the lines of stones tend to be parallel. In arctic areas where stone polygons are forming at the present time, an increase in slope results in the reorientation of the polygons into parallel streams of fragments. The presence of this kind of patterned ground is associated with cold frost climates, and in temperate zones is usually interpreted as evidence of mass movements that occurred during or immediately following a glacial advance.

A further line of evidence is the striking adjustment between boulder distribution and topographic form seen in the larger relief features, the lobate terraces in the western part of Compartment I. Boulders are absent from the steep slopes, but form concentrations at the foot of the steep slopes and in the drainways at each side that may represent the contact between the edge of slipped material and the undisturbed surfaces. A few boulders occur on the terrace flat and on the slope about it. The distribution of these boulders is evidence of gravity movements to positions that are now stable. These facts support the conclusion that gravity movement occurred from the upper slopes, either fragment or by mass movement, or by both processes.

Short steep slopes

The lower slopes of the drumloidal hill upon which Compartment I is located consist of steep (25–40% slope) segments alternating with gentler segments (Fig. 2). These abrupt changes in slope appear in places as well-defined terraces, whose long axes lie at right angles to the general slope of the hill. Stones and boulders are almost completely absent from the short steep slopes but are abundant at their bases. No rock crops out in any of the slopes, and a trench through one of the smaller relief features revealed only drift.

On these short steep slopes are smaller relief features 20 to 30 feet in diameter suggesting small slips formed by mass movement or landsliding. A trench was dug through one of these smaller relief features in an area of complex slopes to ascertain whether the surficial deposits would reveal evidence in support of a slip hypothesis. The nature and relations of the soil materials exposed in the trench are shown in Figure 4.

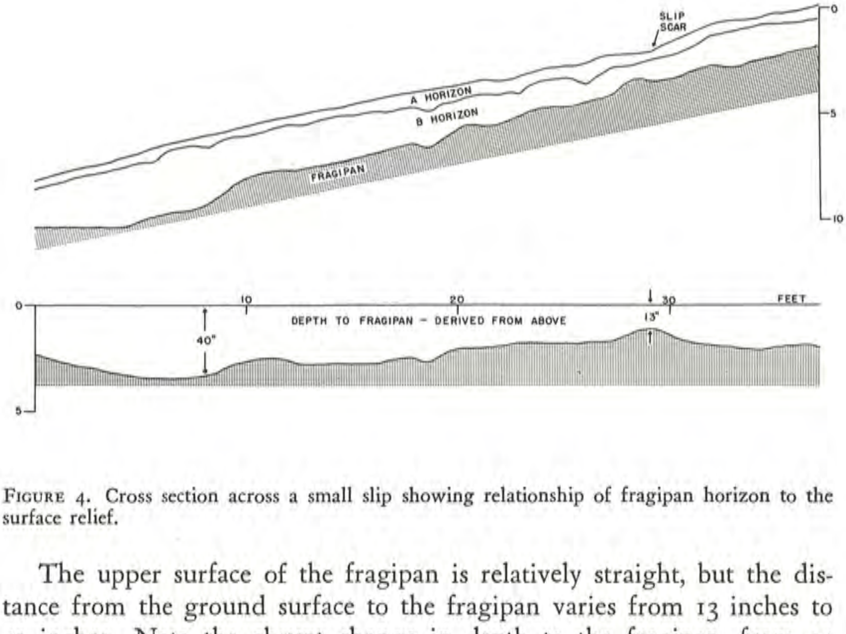


FIGURE 4. Cross section across a small slip showing relationship of fragipan horizon to the surface relief.

The upper surface of the fragipan is relatively straight, but the distance from the ground surface to the fragipan varies from 13 inches to 40 inches. Note the abrupt change in depth to the fragipan, from 24 inches to 13 inches and back to 24 inches near the upper end of the trench. This relationship is better illustrated in the diagram at the bottom of Figure 4, which shows depth to pan from the ground surface.

These relations suggest that the relief feature was formed by gravity movement of a mass of soil material sliding upon the surface of the pan. If this be true, the point of minimum distance to pan probably represents the upper edge of the mass of slipped soil, and the point of maximum distance to pan probably represents the point at which most of the slipped soil came to rest. Upslope from the relief feature, if a slip indeed led to its formation, one would expect to find evidence of a fracture line or crack on the ground surface that would outline the area from which the soils slipped. In fact, from the vantage point of the center of the relief feature, a crescent-shaped line can be detected that extends upslope from the edges of the feature. This line delineates an area of slightly steeper slope, and probably represents the slip scar. The fracture line appears in Figure 4 as a narrow, shallow depression upslope from which the slope steepens slightly.

About 15 of these small relief features, presumably slips, have been found in Compartment I. All of them support forest, some of it old growth. None of them has been formed since establishment of the Harvard Forest, and probably none since settlement in 1733. Small landslides occur at present on steeper slopes such as highway cuts through sandy till, particularly when the till is relatively impermeable to water, and so the mantle in Compartment I on the steeper slopes presumably would be subject to landslides at the present time if the soil became unusually wet. All of the slides show essentially the same surface characteristics, and may have been formed simultaneously. The presence of the more or less continuous fracture line suggests that the features were formed within the relatively recent past. Studies of the reduction of tree-throw mounds in the Harvard Forest, Stephens, (1956), showed that mound and pit microrelief almost completely disappears after about 500 years, which suggests that the fracture lines also would be erased within about the same time interval.

Small slips become especially important to tree growth when several coalesce. The thickened material at the downslope end may not only provide a greater depth of soil for root penetration but may change the water relationships of the soil. An example is at the base of the larger short steep slope in the 8-acre study area. Here several small slips have occurred and the thickened material has blocked off a former drainage-way, leaving a small concave wet area. Another example is the solifluction mantle over the glaciofluvial material at the foot of the drumloidal hill. The irregular surface relief indicates that a good deal of this mantle resulted from sudden small slips rather than gradual movement downslope particle by particle.

The short steep slopes shown in Figure 2 are much larger relief features than the one which was trenched, and the scarcity of data concerning their internal structure makes their origin more obscure. Soil pits show that the upper surface of the fragipan roughly parallels the surface of the ground at a depth of about 24 inches, which suggests that the pan formed after the formation of the large relief features. If so, this means that the large relief features are older than the small ones, because the trench showed no such close relation between pan surface and ground surface.

Thus, the origin of the large relief features presents problems of a different sort. Their greater age raises the possibility that processes characteristics of climatic regimes that differ markedly from those of the present resulted in their formation. Two hypotheses are advanced in the following sections to account for the formation of the large relief features.

Landslide hypothesis

The surface configuration of the larger relief features on the lower slopes of Compartment I strongly resemble those of the smaller features. Thus, the large lobate terraces at the southern end of the 8-acre area consist of two steep short slope segments alternating with two segments of much gentler slopes (Fig. 2). If the lowermost of the terraces resulted from a landslide of three or four acres, the steep slope of the upper terrace would represent the slip scar with the fracture line at the top of the steep slope.

If the steep slope of the uppermost terrace represents the slip scar of a large landslide, further adjustments to the new angle of slope thus created might have taken place. In Compartment I, many of the small relief features attributed to mass movement over the fragipan are located on these postulated slip scars, including that which was trenched and previously described (Fig. 4).

The mass movement hypothesis was first applied to lobate terraces in the Harvard Forest by Stout (1952). He attributed these lobate terraces to processes resulting from cold climates, which caused gravity movements of surficial materials under the influence of ground frost. He stressed the similarity of the terraces in the Harvard Forest to landforms now developing in parts of the arctic and subarctic regions, and postulated their formation during Wisconsin glaciation in a periglacial climate. This hypothesis satisfactorily explains the shape of the short steep slopes as well as their appearance in pairs and their orientation parallel to the slope.

Ice margin scarp hypothesis

This hypothesis, proposed by A. L. Washburn in 1961 after a visit to the area, explains the short steep slopes as scarps resulting from the cutting by moving water which flowed between the margin of the melting glacier and the hillside of the drumlin. Following advance of the last glacier the ice in most of New England is thought to have remained in place and melted by stagnation. As the ice melted the hills gradually became exposed. The hillsides were in contact with the melting ice and at this point of contact moving water in the form of meltwater streams from the bordering ice readily could have cut scarps into the face of the hillside. These scarps when formed may have had about the same shape as they do now or may have been nearly vertical and subsequently achieved their present slope as a result of slumping.

If ice margin streams did cut the short steep slopes, a general gradient toward the south would be expected because of the southward movement of meltwater from the ice that filled the long north-south trending valley bordering the hillside. To demonstrate such a slope, a detailed contour map of the whole compartment would be needed. Such a map is not available but a 3-foot contour map of the 8-acre tract (Hatheway, 1954) does show such a slope to the south at the base of both of the short steep slopes in the southern part of the area.

Of these two, the landslide hypothesis is favored.

Stone and boulder distribution

Stones and boulders[1] are numerous all over Compartment I. In this respect the tract is typical of much of the land in New England, particularly the areas where the glacial till has been derived in large part from granitoid rock. In the 66 acres of Compartment I the stones and boulders visible on the ground surface number in the thousands. Almost all of them are granite, and they range in size up to 10 feet in greatest dimension. Most of the rock fragments range in diameter from 10 to 12 inches, but there are many large boulders.

The stones and boulders are not randomly distributed over the area, as is shown in Figures 5 and 6. Their distribution was examined in detail in the belief that the forces controlling their distribution are related to the geomorphic processes that moulded the slopes, established the drainage patterns, and affected soil formation. These processes also

[1] A stone is a rounded or subrounded rock fragment ranging in diameter from 10 to 24 inches. A boulder is a rounded or subrounded fragment larger than 24 inches. Soil Survey Manual. U.S.D.A. Misc. Pub. 18, 1951.

affect the composition and growth rates of the present forest, because they produce local variations in the habitats, Sharpe (1938) and Flint (1957) have discussed the transport and sorting of materials to form such features as stone stripes, stone rings, and stone polygons. The stone and boulder patterns found in places on the 8-acre study area are similar to those described as block stripes which apparently collected in gullies during the downhill creep of soil.

Stoniness varies from stone-free to a nearly complete cover of stones and boulders (Fig. 7). Major concentrations of boulders occur at the bottom of steep slopes and in areas that now represent intermittent waterways. The entire area would be classified as very stony in soil survey mapping.

The conspicuous concentrations of stones and boulders at the base of the short steep slopes (Figs. 6 and 8) may have been formed when the stagnating ice sheet filled the valley. Stones and boulders freed from the melting ice may have been concentrated on the ice-marginal streams in their present positions. However, study of the orientation of large boulders throughout the compartment suggests gravity movements of the rock fragments on the surface of the ice-free slopes.

The large boulders vary considerably in size, averaging 4 to 5 feet long by 3 to 4 feet wide and 3 to 4 feet thick. A few boulders measure 10 to 12 feet long, about 6 feet wide, and 5 to 6 feet thick. Many of the large boulders are ellipsoidal in outline (Fig. 9). The long axis of most of these boulders is oriented up and down slope — at right angles to the presumed direction of glacial flow — and they tend to form lines of boulders, also up and down the slopes. Figure 10 shows profile and plan views of a line of large boulders. Note that the long axis of most of the boulders is not parallel to the ground surface, but that the downslope end is high in the air. This position is often seen in Massachusetts, and probably indicates slow downslope movement while partially submerged in the soil. Only one extremely long and narrow boulder on the 8-acre study area is oriented with its long axis parallel to the slope contour. The long axis of all other boulders is oriented up and down slope, and this orientation indicates movement since deposition. Figure 11 shows a boulder oriented with its long axis up and down slope, and Figure 12 shows a large boulder with its following train of stones and small boulders.

Some of the large boulders have mounds of soil at their downslope ends somewhat resembling snow pushed before a snowplow, and triangular depressions at the upslope ends with the apexes pointed upslope. These depressions are parabolic in profile and extend upslope 10

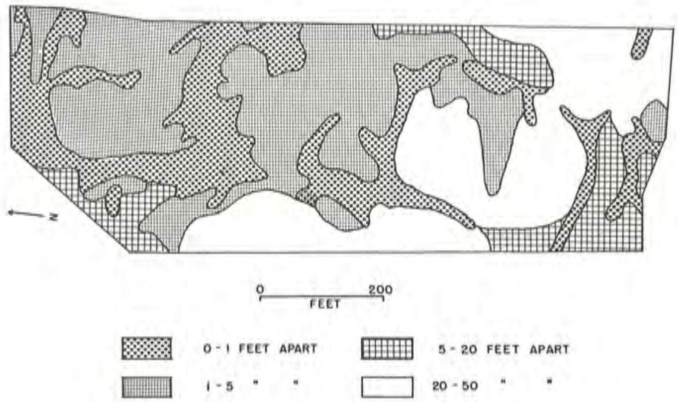


FIGURE 5. Distribution of boulders and stones on the 8 acre tract.

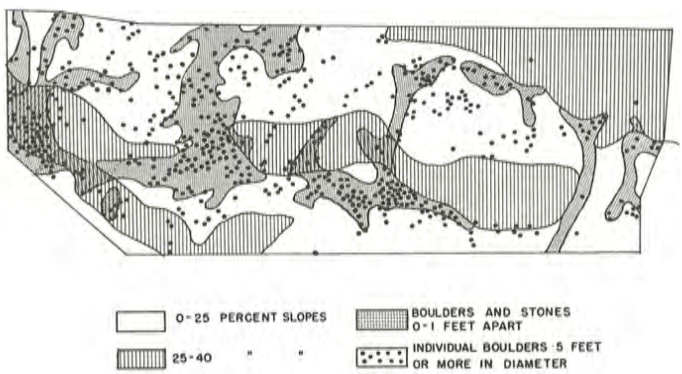


FIGURE 6. Location of individual large boulders, closely spaced boulders and stones, and steep slopes on the 8 acre tract.

FIGURE 7. Nearly complete cover of boulders and stones in the 8 acre study area.

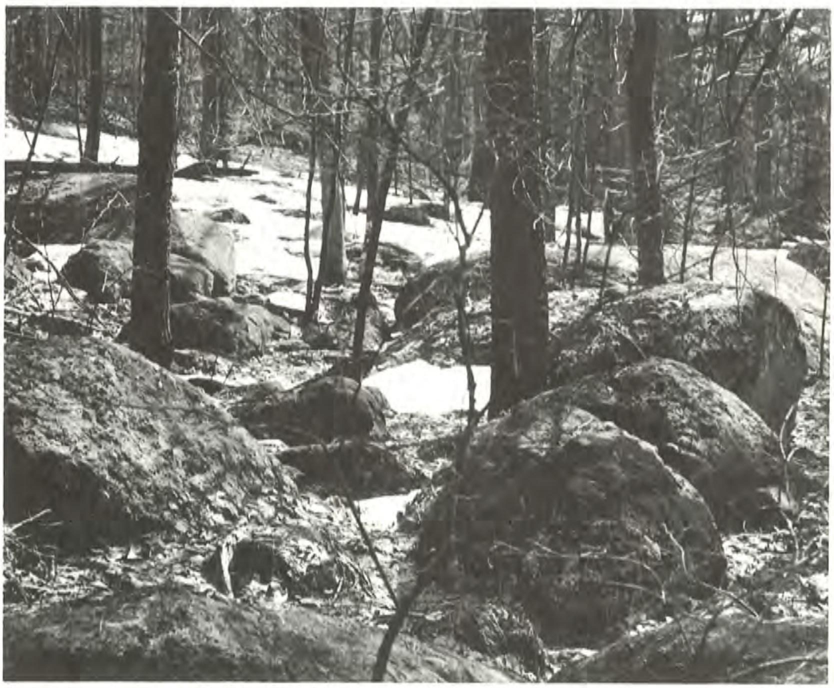


FIGURE 8. Concentration of large boulders at the base of a short steep slope.

FIGURE 9. Ellipsoidal boulder in characteristic position on a slope of the 8 acre study area.

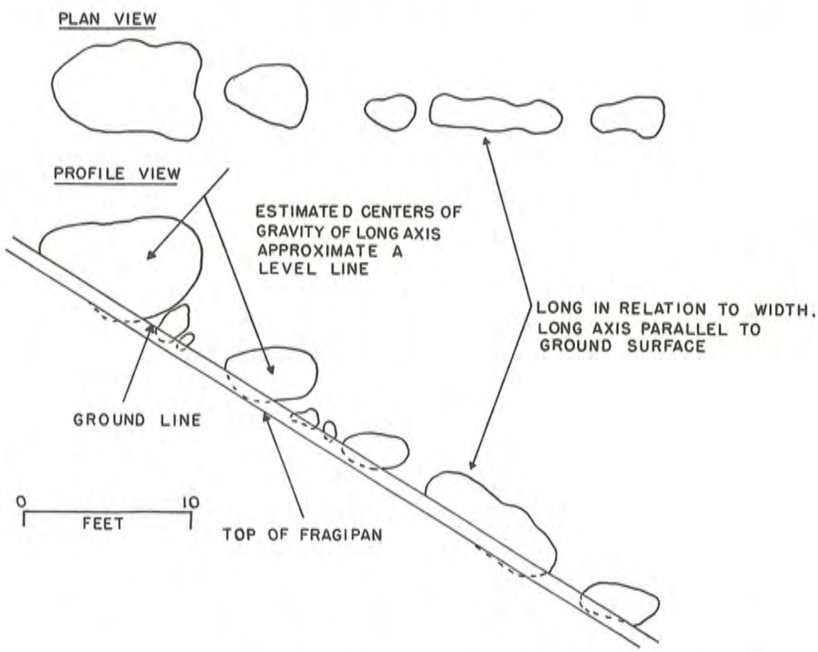


FIGURE 10. Characteristic orientation and position of boulders and stones on slopes of the 8 acre study area.

Figure 11. Large boulder oriented with its long axis up and down slope.

Figure 12. Large boulder with a following train of small boulders and stones.

to 20 feet. The presence of these well-defined mounds and depressions as well as the absence of stones and small boulders from the depressions suggest rather recent movement of these large boulders.

Hypotheses to explain the present distribution of stones and boulders

The pattern and orientation of stones and boulders in the study area were the features which first drew attention to the rather extensive solifluction that has occurred and its influence in developing the present landforms. Several hypotheses, based on features evident in several parts of the study area, were developed to explain the present distribution of stones and boulders.

The two parallel areas of 25–40 percent slopes in the southern half of Figure 6 are parts of a large "slip" so-called, where a relatively large section of land moved downslope. Two intermittent streams or waterways formed in the cracks or edges of the slip. In Figure 6 these waterways are the long narrow areas, approximately at right angles to the steep slopes, where boulders and stones are 0–1 feet apart. Solid concentrations of boulders appear at the foot of the slip, but very few stones are on the steep face of the bulge of the slip. Many stones are on the gentle slope at the heel of the slip, and practically no stones are on the backslope where the slip originated.

A distinct long, narrow, stone-free area is at the junction of the slip and its backslope. Within very narrow limits this area separates those stones and boulders that were on the slip when it occurred from those stones and boulders which have since moved downslope onto the eastern section of the slip. This postulation is based on the fact that large stones and boulders of varying size occur on the eastern side. The stones and boulders would have moved downslope had the slip not occurred. Assuming random sizes of stones and little or no blocking, the stones and boulders would have a natural segregation according to physical laws and no clearly defined path or stone-free area would have occurred. The general flow of boulders after the slip occurred was down the intermittent stream on the south side of the area. Several large boulders are now located along this waterway. The slope is relatively steep and these boulders are in position to continue movement at any time.

The backslope of the slip has very few stones or boulders. This is to be expected since this backslope is steeper than the prevailing slope uphill from it. The area also could have been made stone-free by slipping downslope at the time of colluvial movement of soil material. All boulders coming over the edge of the backslope after the slip occurred would under favorable conditions for movement tend to accelerate their forward movement and to concentrate at the juncture of the steep backslope and the more gently sloping heel of the slip. The general degree of slope of the hill is lower than that of the backslope of the slip. A few large boulders had started to move down over the bulge of the slip. Those forces triggering the action must have been reduced at this time, otherwise these boulders would have continued their movement down the slope.

The central portion of the study area has many boulders dispersed over it. Many boulders have reoriented their path of travel toward the concave area on the south side of this central area. A stone-free area occurs on one very slightly steeper section. When boulders moved onto this slope they continued their forward movement, and formed a solid mass in the waterway along the south side of the area. Movement downslope continued until the entire declivity was solidly blocked with boulders to the area of lower gradient along the bottom of the steep slope.

One area on the steep slope had several boulder "strings." (The term "string" is used here to indicate a single line of boulders and large stones.) Boulders and stones are lined in a single path down the slope (Fig. 10).

The position of one of the larger boulders in relation to the soil profile was studied by digging trenches parallel to the contours upslope and downslope from the boulder as well as at right angles to the contours underneath the boulder (Fig. 13). This boulder, about 7 feet in diameter, was oriented with its long axis up and down slope and was level rather than being parallel to ground surface. Soil material was mounded in front of the boulder and a depression was present upslope. Part of the boulder rests upon the surface of the fragipan, although most of its lower surface lies in the upper parts of the profile. A pronounced depression in the upper surface of the fragipan is visible upslope from the boulder, and the mound of soil downslope from the boulder shows typical Brown Podzolic development. The depression upslope from the boulder, which appears as a groove in the surface of the fragipan, may have originated as a stream channel or as a gouge or depression formed by movement of the boulder. The mound of soil piled in front of the boulder strongly suggests that the depression was formed at least in part by movement of the boulder. Stephens' (1956) studies of the rate of soil development in tree-throw mounds in the area suggest that the profile in the sandy loam material would take more than 500 years to develop. Well-developed Brown Podzolic soils on sandy materials in

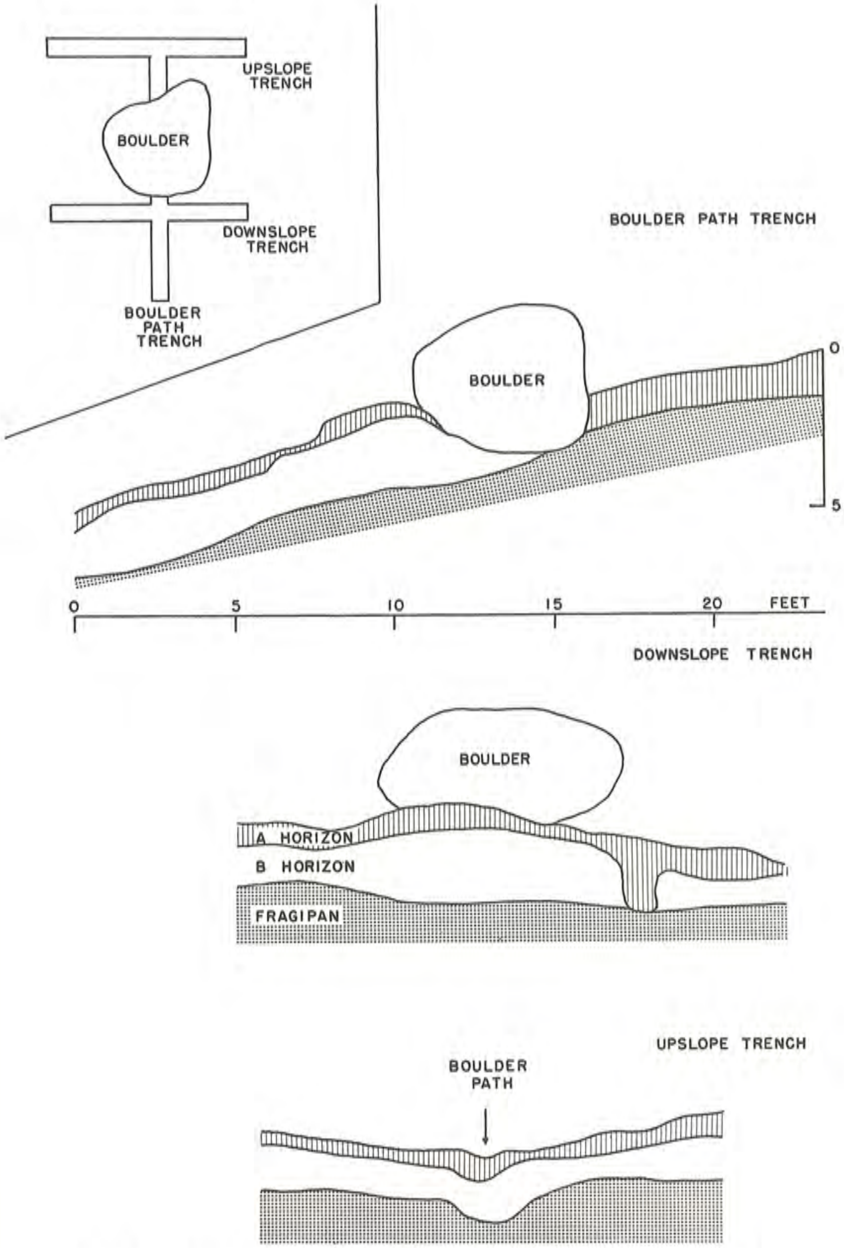


FIGURE 13. Relationship of a large boulder to the underlying fragipan horizon.

eastern Massachusetts are found over archaeological materials dated at 4,000 years old (unpublished data, Soil Conservation Service, U. S. Dept. Agri.). Therefore, the soil profile in the mound downslope from the boulder probably required 500 to 4,000 years for development.

The northeastern part of the central section of the study area has a relatively uniform slope on which large numbers of stones and boulders have accumulated. Slight changes in microrelief have caused some very small areas to be relatively free of stones and boulders. The area of maximum boulder accumulation occurs in the waterway along the southern edge of this section and at the bottom of the steep slope.

The northern section of the study area is largely very stony and very bouldery. The slope is relatively uniform with only minor convex or concave surfaces. Several concentrations of boulders occur in what are now waterways, but, in the main, the entire area expresses the result of widespread downslope movement. Large boulders and varying sizes of stones are intimately intermingled. These concentrations of stones caused a blocking effect and prevented segregation and concentrated movement of large boulders down the slope.

There are several distinct lines of boulders on this area. In most instances the large boulders have several stones directly in front of each boulder. In some instances water flowing down the boulder path has removed soil material from one side of the channel, sometimes forming a branching stream. This has apparently caused a boulder in the main channel to reorient, tilt, and change its direction. In some instances it appears that boulders moving down the channel have passed other boulders and in this manner a pattern of boulders has developed that approximates an alluvial fan.

Definite concentrations of boulders in relation to slope and amount of blocking, and concentrations in what are now waterways, or particular concave sections occur all over the compartment. Only an occasional large or extremely large boulder (roughly 8 to 10 feet square, above ground) occurs near the top of the slope, and these boulders are completely blocked by a concentration of large stones on the downslope side.

A small saddle occurs at the top of the hill and water in this depression drains to the north and to the south. Large boulders have moved the short distance necessary to concentrate in the saddle. Little or no movement of the boulders along and out of the saddle occurred in this section due to the low gradient. Downslope movement of boulders occurred immediately outside the saddle where the slope steepened onto the main slope of the hill.

The rough count of boulders and the measurement of land areas of several sections of this kind, where boulder movement had apparently been definitely restricted, gives the average number of large boulders per unit area deposited by the glacier on this particular site. The number of large stones and boulders deposited varies somewhat within the area studied, but general examination of the number of large boulders per unit area in narrow depressions showed that a relatively uniform number of large boulders had been deposited per acre. The few boulders on upper slopes, increasing numbers on the middle slopes, and concentrations of stones and boulders at the base of the slopes and in waterways strongly suggests movement since deposition.

The nearly complete absence of stones and boulders in former fields of Compartment I can be explained by man's activity since settlement in 1733. But the present orientation of most of the large boulders, the presence of strings of boulders up and down slope, the presence of depressions upslope and mounds of soil immediately downslope from some boulders suggest gravity movement of the rock fragments since their deposition in or on the drift. Furthermore, the fact that the trenched boulder as well as other stones and boulders exposed in soil pits in the area rest upon the upper surface of the fragipan suggests that the fragments slid upon the fragipan or its precursor, the dense, platy till that constitutes the drumloidal hill.

However, none of these lines of evidence indicates movement of more than a few feet. Claim of a greater distance of movement depends upon conclusions drawn from the present field relations of the stones and boulders.

The distribution of most of the stones and boulders shows a close adjustment to topographic form. Thus, most of the concentrations of fragments are found at the base of steep slopes and in drainways; and the widely spaced fragments are found mostly on knolls and other convex areas. The closeness of the adjustment between topographic form and distribution of fragments suggests widespread gravity movements, and the increasing closeness of boulders downslope suggests that some of the fragments have moved relatively long distances.

Concentrations of large boulders do not always coincide with concentrations of stones. This difference suggests that large boulders move at different rates than do stones, or under the influence of different processes. Borrow pits and deep road cuts in the drumlins of Massachusetts show that most of the stones in the hard platy till range from 10 to 12 inches in diameter, and that boulders are almost completely confined to the surface layers. In Compartment I, the boulders rest on the surface of the fragipan, which ranges from about 20 to about 30 inches in depth from the ground surface. Thus, stones and small boulders often are completely encased in soil materials overlying the fragipan, but most of the volume of the larger boulders is above the ground surface. The resistance to movement of the fragments provided by the soil is less for large boulders than for small ones, and much less than for stones. Large boulders probably moved independently of the soil materials, but gravity movements of fragments enclosed in soil probably take place mostly as mass movements or landslides. The large boulders, therefore, might move under conditions that inhibit movement of small boulders and stones. The largest boulders tend to be concentrated on the lower slopes of the hill, and the proportion of ellipsoidal boulders seems to be higher here. These field relations suggest that the larger boulders, once movement begins, move greater distances than smaller rock fragments, by reason of their great mass and the resulting momentum, the smaller percentage of their volume that is subjected to the friction of the surrounding soil, and their streamlined shape.

No evidence of gravity movement of rock fragments at the present time has been found. Many trees are growing upslope from boulders, with their stems so jammed against them as to take the form of a mirror-image of the boulder. Yet none of these deformed stems has been found with air space separating it from the boulder. At the present time boulders on slopes of as much as 40 percent gradient are stable, yet the evidence indicates that boulders have moved in the past on slopes of less than 10 percent gradient.

If many of the relief features were formed by mass movements, the boulders certainly did not come from the almost completely stone-free platy till exposed in the slip scars. Thus, if the rock fragments now found at the foot of the slope came from points upslope from the terrace, most of them reached their present position prior to the mass movement or were concentrated near the fracture line prior to the landsliding. Once the relief feature existed, a movement of individual fragments across the terrace flat would be blocked, and moving boulders would be diverted into the narrow depression around the edge of the feature or immobilized on the flat. Most of these narrow depressions are completely blocked with stones and boulders.

The strings of boulders that occupy the shallow drainways tend to coalesce at the base of the long slope and form fan-shaped deposits analogous to alluvial fans. These strings may have formed by gravity movement of individual boulders into pre-existing drainways. Alternatively, one large boulder may have moved downslope, grooving the hard underlying till, and creating a path to which subsequent boulders adjusted. If this be true, a large part of present drainage patterns on the smooth slope of the hill are the result of gravity movement of boulders.

That the movement of rock fragments in Compartment I is related to the presence of a fragipan or dense till is best demonstrated by the glaciofluvial sands and gravels in the western part of the area, which lack fragipans. This deposit also almost completely lacks boulders, although a line of large boulders lies immediately upslope from the sand and gravel deposit at the foot of a steep slope that constitutes the face of a lobate terrace. A trench across this boulder front revealed that the boulders lie on a deposit of loamy colluvium, which in turn overlies sand and gravel. The colluvium contains a fragipan, which makes the colluvium appreciably wetter than the sand and gravel. The downslope movement of the boulders was arrested at the edge of the sand and gravel, either because the bearing surface represented by the fragipan was lacking, or because of the sharp change in texture of the soil materials. Texture affects frictional properties as well as drainage and moisture regimes. If the bearing surface were a layer of ground ice, the boundary between till and glaciofluvial deposit probably would provide a break in the level of the frozen layer, because the differences in texture produce differences in freeze and thaw rates as well as differences in frost penetration.

SOILS

Great soil groups

Most of the soils of Compartment I are members of the Brown Podzolic great soil group. These are the principal soils on freely drained deposits in southern New England. They are classed as Orthods at the suborder level in the proposed new classification. (Soil Survey Staff, Soil Conservation Service, 1960, Simonson, 1962) Soils of the Brown Podzolic group are generally well drained and well aerated in the upper 18 to 24 inches. Movement of water is downward in the upper part but is lateral in the lower part if the soils have slowly permeable underlying layers. Unplowed soils have a 2–3-inch dark brown very friable surface soil or A horizon. The subsoil or B horizon is 18 to 24 inches thick, has a distinctly more intense color in the upper part than in the lower, and the color fades gradually with depth. The upper part of the subsoil is always friable but many Brown Podzolic soils, especially those on deposits of medium texture, have a very firm, brittle, dense horizon in the lower part of the B horizon called a fragipan.

The substratum of Brown Podzolic soils under the A and B horizons varies widely in properties. It may be loose as in many sandy glaciofluvial deposits or very firm and dense as in certain kinds of glacial till deposits. It may be very coarse or very fine textured.

Both free iron oxide content and organic matter decrease with depth in the B horizon. The process that leads to the stronger color and the greater amount of free iron oxide and organic matter in the upper part of the B horizon is dependent on the downward movement of soil moisture. This moisture carries soluble products from the A horizon and deposits them in the B horizon. The surface of the soil under forest trees generally shows an appreciable thickness of organic matter. Movement of water through this organic matter dissolves substances which have been rendered soluble by biologic action. These in turn combine with iron and aluminum compounds which have been released from the minerals present in the A horizons. The complex organo-inorganic substance — a chelated compound — moves downward and is precipitated in the B horizon. The resulting material is deposited around and between mineral particles in the B horizon and is responsible for the strong brown or reddish brown color of this horizon. This deposition is concentrated in the upper part of the B horizon and this accounts for the stronger color in this part of the soil. The deposit around and between the mineral particles serves as a sort of sponge and helps retain water. It also serves as a source of organic matter to provide energy and nutrients for a large population of micro-organisms and feeding rootlets.

In the wet areas of Compartment I the soils are poorly and very poorly drained and are members of the Low Humic Gley and Humic Gley great soil groups respectively. In the proposed new soil classification both are Aquepts. In these wet areas the ground water is close to the surface and the soils are water-logged.

Humic Gley soils have 6 to 8 inches of dark mineral soil on the surface and in some places a muck layer several inches thick. Low Humic Gley soils have dark gray or black Al horizons that are 2 or 3 inches thick. Mottles of gray and reddish brown occur in the lower horizons of both soils and indicate areas that have undergone local oxidation and reduction as a result of the periodic waterlogging.

A fragipan is present in these wet soils. Below the fragipan at depths of 5 to 6 feet lies very firm dense glacial till.

Water tables in Low Humic Gley soils are high for a longer period than in better drained soils. The root zones may be saturated a couple of weeks longer in the spring and become wet a week or two earlier in the fall.

Soil series

Five soil series occupy practically all of the 8-acre study tract. Three others occur in small isolated patches of a few square feet. Distinguishing characteristics of the 8 soil series are shown in Table 1. Chemical and physical properties for several of these soils are given by Prince and Raney (1961).

By far the greater portion of the area is covered by 3 soils developed from the firm basal till which covers most of the area. These soils encompass the whole range of wetness from well to very poorly drained and are members of the Paxton, Woodbridge, and Whitman series.

Paxton is well drained and essentially free of mottling in the upper 18 or 24 inches. It is good soil for the growth of most kinds of trees. Woodbridge is moderately well drained and has mottling within 12 to 14 inches of the surface. It is wetter than the Paxton but still is a good soil except in the wettest years. Associated with the Woodbridge are the Ridgebury soils which are poorly drained. In the 8-acre tract there are only one or two small patches of the Ridgebury soils. In the places where the Ridgebury would be expected there is a marked mound and pit relief from former windfalls and in these areas Woodbridge soils are

TABLE 1

IMPORTANT CHARACTERISTICS OF THE SOIL SERIES ON THE 8-ACRE TRACT

Soil series	*Parent material of B horizon*	*Differentiating characteristics*	*Natural drainage*	*Great soil group*
Paxton	Gravelly fine sandy loam glacial till derived principally from schist and granite.	Yellowish brown B horizon over strongly developed fragipan. No mottles.	Well drained	Brown Podzolic
Charlton	"	Like Paxton but fragipan weak or absent.	"	" "
Woodbridge	"	Like Paxton but with a few mottles in B horizon above the fragipan. (The somewhat poorly drained phase is a little wetter than the moderately well drained soil.)	Moderately well drained	" "
Ridgebury	"	Strongly mottled olive brown B horizon overlain by thin A1 and thin mottled gray A2g horizons; underlain by strongly developed fragipan.	Poorly drained	Low Humic Gley
Whitman	"	Strongly mottled olive brown or gray B horizon overlain by thick A1; underlain by strongly developed fragipan.	Very poorly drained	Humic Gley
Barnstead	Gravel and sand glaciofluvial deposits principally from schist and granite.	Reddish brown or strong brown color throughout solum. Fragipan absent. No mottles.	Somewhat excessive	Brown Podzolic
Brimfield	Fragmented rust colored mica schist bedrock with thin mantle of fine sandy loam glacial till.	Reddish brown color throughout solum and many intermixed angular fragments of weathered mica schist. Fragipan absent. No mottles.	" "	" "
Enfield	Silty aeolian mantle 2–4 feet thick, over gravel and sand.	Upper B horizon silty, lower B horizon extends downward several inches into underlying sand and gravel. Fragipan absent. No mottles.	Well drained	" "

in the mounds and Whitman in the pits. Charlton soils are very similar to the Paxton but the fragipan is weakly developed or is deeper than 30 inches from the surface. The Charlton soils occur where the sand and gravel deposits are mantled by colluvium.

The soils developed from the gravelly deposits which have no colluvial mantle are gravelly throughout. They are well or somewhat excessively drained Brown Podzolic soils and members of the Barnstead series. The rounded pebbles at the surface and in the upper horizons indicate that they have developed almost entirely from the underlying water-sorted deposits. The Charlton, Paxton, and Barnstead soils in this footslope area of Compartment I are intimately intermingled and occur in such small areas that it would require very painstaking work to map them individually. In the detailed soil map of the 8-acre study area (Fig. 14), the soils of the footslope area are mapped as a complex.

In a few spots in this footslope area the soil is shallow over soft weathered reddish mica schist, and is a member of the Brimfield series. These areas also were too small to be shown on the soil map.

Silt overlies the sand and gravel deposit in a few places on the footslope. These areas are very small. The upper part of the soil profile contrasts sharply with that of other soils because of the absence of pebbles and stones. These soils with silty solums are members of the Enfield series and the silt presumably is of aeolian origin.

Figure 14 is a soil map of the 8-acre study area. This map was made by examining soil pits established on a 100-foot grid with supplemental information from auger borings between the pits. Pits had been established previously in a grid system for water table measurements by Hatheway (1954). These were cleaned and enlarged to about a 2-foot diameter. Detailed descriptions of about two thirds of these pits were made and soil-type identifications were made for all with a record of depth to any contrasting horizon such as bedrock, pan, or gravel. Approximately 3 or 4 borings within each 100-foot square were made in addition to use of the 4 soil pits already at the corners of the square.

The criteria used in determining boundaries between soils of the various degrees of drainage in the Paxton catena were color relationships of the several horizons and the presence or absence of mottling. Depth to pan was not used as a criterion because it could not be determined accurately with an auger. Color, presence of significant quantities of mica, and presence of underlying sand and gravel were used to locate the boundary between the Charlton or Barnstead soils and those of the Paxton catena. The large scale of the base map, 66 feet to the inch, and the grid made it possible to delineate soil areas in a high degree of detail.

Precise map locations could be easily made, but soil changes were often very gradual. Consequently, gradational areas of varying widths occur along each boundary line.

Several conditions in the area added to mapping complexity. Tree-throw mounds are numerous over the whole area and almost touch in many places. These, together with numerous boulders, made it difficult to decide just where to examine the soil to evaluate the average condition. After trial mapping, it was decided that soil areas 10 feet or less wide should not be shown on the soil map unless they were highly contrasting with the surrounding soil. Boundary accuracy on the soil map, therefore, is within 5 feet in some instances and 20 to 30 feet in others.

In general, the well-drained soils have slope gradients of from 15 to 30 percent with rather marked variations within this range over short distances. The wetter soils range from about 5 to 15 percent in gradient.

The Charlton-Paxton-Barnstead complex area at the foot of the slope was handled as one map unit. All the soils in this area appear to be underlain by sand and gravel but there is marked variation in thickness and character of the solum within short distances.

On the wettest areas of the 8-acre area mounds and pits resulting from former tree-throws are more numerous than in the drier areas. The soil in these wetter areas is a complex of Woodbridge fine sandy loam, somewhat poorly drained phase, and Whitman loam. Relief of the mounds and pits is about 1 to 2 feet, and this is sufficient to cause noticeable differences in the soils. Whitman loam is in the wet pit areas, whereas the somewhat poorly drained phase of Woodbridge exists on the drier mounds. The two cannot be mapped separately except at a scale large enough to show individual mounds and pits. Ridgebury soils, intermediate in wetness between Woodbridge and Whitman soils, are rare on the 8-acre area, presumably because of the microrelief.

Characteristics and origin of the fragipan

The fragipan horizon is thought to be especially important in the development of landforms and forest in Compartment I and is referred to repeatedly throughout the report. For this reason, the characteristics of the fragipan are described in considerable detail. The horizons of the soil above the fragipan, of course, are important also because they are the ones in which most of the moisture is stored and in which most of the tree roots are located, but details regarding these horizons in these same or similar soils are available elsewhere (Bourbeau and Swanson, 1954; Lyford, 1946; Prince and Raney, 1961; Swanson et al., 1952, Tamura, 1956).

The fragipan has three outstanding characteristics: hardness in place even when wet, platy structure, and brittleness of individual platy structural units.

It is so hard that a pick has to be used to loosen it, and in this respect it contrasts in consistence greatly with the friable soil materials in the horizons above. Material in these upper horizons can be removed readily by a shovel.

The platy structure is apparent when the soil material is loosened from the top because it first breaks out into flattened structral units with fairly well-defined faces. The larger of the platy structural units are 5 or 6 inches long, 3 or 4 inches broad, and 1 or 2 inches thick. These are relatively weak and separate still further with only moderate lateral pressure into smaller flattened plates 1 to 1½ inches long, 1 to ½ inch wide, and ¼ to ½ inch thick. These platy structural units have nearly parallel faces at top and bottom but tend to be a little thinner at the edges than in the middle. They are brittle even when wet and require considerable force to break.

The plates are arranged in layers parallel to the surface of the ground. Each small plate is discrete and not cemented to the others so pressure from the side readily separates them along a line of weakness in a plane parallel to the surface. By contrast, there are few vertical lines of weakness. Seen from the top, the platy peds overlap both at the ends and sides. This is one of the main reasons for the hardness of the soil material when it is removed from the top down. The slightly thinner edges of the overlapping peds allows a very tight fit and this causes the material to be very rigid in place even without cementation between peds. This is not unlike the rigidity of a dry wall constructed of flattened stones.

The flattened surfaces of the platy peds are fairly smooth so when fitted together there is very little continuous pore or channel space between them. This is one reason for the slow permeability to water. The permeability of the individual ped is also slow and 3 or 4 seconds is required for a drop of water placed on the surface to soak into a moist ped.

A coarse weak prismatic structure is another feature of the fragipan in the study area. It is more noticeable in some places than others. The prisms are 12 to 24 inches on a side and are roughly hexagonal in horizontal cross section. The faces of the prisms are coated with about a ¼ inch thick layer of grayish-colored (2.5Y 5/2) [1] friable loamy material about the same in texture as that which makes up the interior of the prisms. Generally, just under the grayish coating is a reddish brown

[1] The numbers and letters in parentheses are the Munsell notations used for colors.

or strong brown (7.5YR 4/4 or 5/6) cemented coating ⅛ to ¼ inch in thickness. The interiors of the prisms are made up of the olive brown (2.5Y 4/4) or olive (5Y 4/4) platy brittle loam just described. This is generally faintly mottled with grayish brown (2.5Y 5/2) and yellowish brown (10YR 4/4). Mottled areas are irregularly shaped and 1 or 2 inches in diameter. Some are between plates but some actually penetrate the plates.

When the overlying horizons are removed, the polygonal outline of the prisms is apparent because of the color contrast between the grayish and reddish deposits on the face and the olive interiors. On the face of the soil pit the prism borders appear as vertical gray streaks bordered by reddish brown on either side.

Occurrence of the vertical gray-coated faces of the prisms is probably important to tree growth. Tree roots do not penetrate into the main body of the fragipan horizon. When they strike the hard brittle material they fan out sidewards in a rather irregular manner and tend to end in a brush-like mass. Roots do penetrate the fragipan along the friable grayish material that borders the prism faces and may extend to depths of 6 or 8 feet. In general, roots occur only in the grayish material and do not radiate from this to the interior of the prisms even though the physical resistance to root penetration along the horizontally aligned platy faces is not as great as resistance to penetration vertically into the interiors. In part, root penetration away from the softer gray outer border is prevented by the thin but cemented reddish inner border. This reddish border has been shown by Gile (1958) to be higher in free iron oxide than the gray border, and it may be cemented too strongly by the iron compounds for roots to penetrate.

The surface of the individual platy ped is slightly porous and has a duller appearance than a ped broken across the face. Use of a 20- or 30-power lens shows that the 0.1 mm. diameter pores are lined with a shiny thin glazed deposit thought to be silicate clay. This same material is also seen around the entrance to the pores and in places on the surface of the peds. Microstudies by Knox (1957), Carlisle (1954) and others have shown this is oriented silicate clay. A good many mineralogical studies of soils of the Northeast suggest that the clay is probably illite. The oriented clay may be the agent that causes cementation and gives the ped its brittleness (Knox, 1959; Yassaglou and Whiteside, 1960).

The pores in the peds are seldom continuous. They branch and rebranch but tend to end up inside the ped rather than continue from one side to the other. Many of the pores observed in broken peds are short and bulbous; they do not empty at the surface.

Thickness of the fragipan in Compartment I is about 18 to 24 inches. The platy structure becomes coarser towards the bottom of the horizon and the soil material becomes less brittle and hard. At a depth of about 40 to 48 inches the underlying firm dense till or C horizon material occurs. Lack of glazing due to clay accumulation and lack of brittleness are criteria which can be used to differentiate the C horizon from the B horizon.

The parent material is a loam or fine sandy loam and is olive brown or olive in color. Under well-drained soils the till itself is not mottled or only faintly mottled. Under the wetter soils the till is mottled in the upper 2 or 3 feet of the C horizon and the material is solid colored below and essentially free of mottles.

At present, the most plausible hypothesis is that the brittleness of fragipans is the result of segregation of a very small amount of nonexpanding kinds of clay in the interstices of sand particles. Fragipans do not develop if the material is either very clayey or very sandy. Typically they are developed from loams, sandy loams, and silt loams. In these medium-textured soils the various sized mineral particles seem to fit together closely and make a very dense matrix. In this dense matrix, only a little clay moved to the interstices of the sand particles and oriented there as thin films could provide the cementing qualities that make the peds brittle. When a great amount of clay is present the pores may be clogged with clay and the clay may not be oriented (Brewer and Haldane, 1957).

Yassaglou and Whiteside (1960) recently studied soils in Michigan in which the fragipans closely resemble those in the soils of Compartment I. They suggest the following steps in the formation of fragipans.

1. Removal of part of the clay, particularly the expanding kinds of clay.

2. Contraction, after the removal of clay and soluble substances, by forces such as gravity, pressure of roots, wetting and drying, and freezing and thawing. This contraction, probably in the early stages of soil development, results in the formation of verticle and horizontal cracks.

3. Rearrangement of matrix substances, particularly the segregation of nonexpanding clay into bridges which connect coarse silt and sand grains.

4. Possible accumulation of aluminum compounds from decomposing minerals.

Contraction of the material in the fragipan horizon as a result of the removal of a considerable amount of soluble material is possible in these soils studied by Yassaglou and Whiteside because the parent material is calcareous and cavities result when the carbonates are removed by solution. Collapse of the cavities would increase the density of the soil. This hypothesis is less valid as a means of accounting for the denser material in the fragipans of the soils of New England, most of which have developed on non-calcareous materials.

The hypothesis suggested by Carlisle (1954) who studied soils developed on acid materials seems to be more applicable to New England soils. Carlisle thought that the compaction of the soils was a characteristic of the parent material and the cracks were the result of alternate freezing and wetting.

The fact that the cracks are now completely filled with material and are not known to open even in extremely dry weather suggests that these are relict. It is known that freshly exposed medium-textured glacial drift cracks when it is dried under present-day conditions in Northeast Greenland (H. M. Raup, personal communication). Therefore, the single linear cracks may once have extended to the surface. The upper part could have been destroyed by soil-forming processes but the lower part could have persisted. The large size of the prisms or, if there are cracks rather than prisms, the relatively great distance between single non-intersecting cracks suggests that the shrinkage which led to their formation occurs as a result of strains within a fairly large body of material. This shrinkage might be effective in making widely spaced cracks but not noticeable in cores studied in the laboratory.

Platy structure is not characteristic of fragipans alone. It is also characteristic of thick till under the fragipans in medium-textured glacial drift, especially that in the drumlins of New England. This platiness in part could be the result of frost action as postulated by Fitzpatrick (1956), but platy structure is not limited to areas of former permafrost or even to regions of cold climates. A more likely hypothesis is that the platiness is in some way connected to the action of ground water.

FORESTS

Compartment I is completely forested. All but two acres of the area is covered with naturally regenerated stands of predominantly hardwood species, of diverse composition and age. A pure stand of red pines, planted in 1925, is located in the southeast corner of the compartment. The naturally regenerated stands range in age from less than 25 years to more than 100 years. The youngest stands are those that developed following salvage operations in areas severely damaged by the 1938 hurricane. The oldest stands, in the northwestern half of the compartment, are those that were neither cleared for cultivation or pasture after settlement (Fig. 3) nor clear-cut since the land was acquired by Harvard University. Most of the stands, however, originated following the clear-cutting of old-field pine stands between 1908 and 1926.

Almost all of the hardwood stands are referable to the "transition hardwoods" (McKinnon, Hyde, and Cline, 1935), one of three hardwood forest types recognized in the vicinity of the Harvard Forest. About 20 species of trees are present in the canopy, including hemlock and white pine, which are integral parts of the transition hardwoods. Red oak, white ash and red maple are almost omnipresent. Paper birch is a predominant species in most of the area, white pine is a predominant species only in the steeply sloping western part of the area, and hemlock trees are abundant only in the northwestern part of the area. In terms of sawlog volumes, red oak, paper birch, yellow birch, white pine, and hemlock are the most important species.

Case histories of four of the stands, comprising about half of the area of Compartment I, have been presented by Lutz and Cline (1947). Stout (1952) found a relation between the local distribution of red oak and white ash and the depth to the firm till, now recognized as a fragipan, at several points in Compartment I. More recently, Patric (1956) studied and mapped the forest vegetation and the soils in a 20-acre area within the compartment, and showed that the nature of the present vegetation was related to soils characteristics and previous forest operations. None of these studies included the old-growth forest in the steeply sloping western part of the compartment, where Hatheway (1954) made the preliminary investigations that led to the detailed studies described in this report. Therefore, most of the following discussion of the forest is confined to the 8-acre area first studied by Hatheway.

Forest in the 8-acre of detailed studies

The study of the forest in the 8-acre area required a careful description of local variations in the transition hardwood type. None of the existing maps of the forest had been made at the extremely large scale of the base map used in the present study. Therefore, a new set of forest data was collected at a degree of detail comparable to the new map scale of 66 feet to the inch. This map scale focuses attention upon individual trees, and emphasizes the variations within cover types that are defined in terms of the predominant species in a stand.

Several type maps were made independently by different workers at the new map scale. A comparison of these maps showed little similarity, either in cover types or the boundaries between stands, and the system was abandoned. Instead, the location of all stems of each of the 19 species of trees forming the forest canopy was mapped. A quantitative measure of the importance of the various species in the forest, as well as variations in the amounts of wood within the area, was provided by measurements of basal area and volume at more than 50 points within the area.

The stem maps were made possible by Hatheway's soil pits and a base map that showed the location of these pits. By stretching string between adjacent pits to form a rough square, the location of each stem could be plotted by inspection to an accuracy of about 10 feet. Individual maps of stems for each of the 19 species were prepared. In these maps, boundaries have been drawn around trees that grow within 30 feet of each other, and individual stems within the bounded areas omitted.

A total of almost 1,900 stems are present in the forest canopy in the 8-acre area (Table 2). Seven kinds of trees — red maple, white pine, red oak, black birch, paper birch, white ash, and sugar maple — constitute 90 percent of these stems.

Red maple is the most abundant tree (385 stems), and is evenly distributed throughout the area (Fig. 14). Many of these trees are in the lower crown canopy, and are not as conspicuous in the stands as the oaks, birches, and pines. The distribution of red oak (251 stems) resembles that of red maple but the spreading crowns and larger diameter of the oak trees make them striking components of the stands (Fig. 16).

White pine trees (270 stems) grow everywhere on the area (Fig. 14), and form an almost pure stand in the steep western part of the area (Fig. 17). This concentration of pines results, of course, in a scarcity of other species in the western part of the area. Red maple and red oak trees are numerous in this pine stand, but black birch, paper birch, sugar maple,

Table 2

Distribution of Tree Species in Terms of Soil Types

SPECIES				*SOILS (Symbols are those used on soil map.)*											
		No. stems in study area	*% of total stems of all species*	*WCH(25.9%)*		*W(29.7%)*		*MW(22.6%)*		*SP(13.0%)*		*P(8.8%)*	
Common names	*Scientific names*			*no. stems*	*%*	*no. stems*	*%*	*no. stems*	*%*	*no. stems*	*%*	*no. stems*	*%*
Red maple	Acer rubrum	385	20	91	23	102	27	99	26	55	14	38	10
White pine	Pinus Strobus	270	14	132	49	75	28	39	14	15	6	9	3
Red oak	Quercus rubra	251	13	35	14	98	39	60	24	36	14	22	9
Black birch	Betula lenta	205	11	76	37	66	32	24	12	26	13	13	6
Paper birch	Betula papyrifera	197	10	31	16	37	19	78	40	43	22	8	4
White ash	Fraxinus americana	195	10	15	7	35	18	68	35	32	16	37	19
Sugar maple	Acer saccharum	193	10	36	19	72	37	33	17	29	15	33	17
	Subtotals	(1696)	(90)										
Pignut hickory	Carya glabra	39	2	6	15	17	44	16	41	..	..	..	..
Hemlock	Tsuga canadensis	32	2	19	59	4	13	5	16	4	13	..	..
American hop-hornbeam	Ostrya virginiana	29	2	6	21	10	35	4	14	8	28	1	3
Large-toothed aspen	Populus grandidentata	24	1	4	17	8	33	5	21	4	17	3	13
Basswood	Tilia americana	24	1	..	..	11	46	9	38	1	4	3	13
	Subtotals	(148)	(8)										
White oak	Quercus alba	17	0.9	5	29	9	53	2	8	1	4	..	..
Quaking aspen	Populus tremuloides	15	0.8	1	7	1	7	10	67	3	20	..	..
Shagbark hickory	Carya ovata	8	0.4	..	..	1	13	7	88	..	..	..	..
White sassafras	Sassafras albidum	4	0.2	..	..	1	25	..	..	2	50	1	25
Yellow birch	Betula lutea	2	0.1	2	100	..	..	..	..	..	..	..	..
American elm	Ulmus americana	2	0.1	..	..	..	..	1	50	..	..	1	50
Beech	Fagus grandifolia	2	0.1	..	..	..	..	2	100	..	..	..	..
	Total no. of stems	(1894)		(24%)		(29%)		(24%)		(14%)		(9%)	

Scientific nomenclature follows that of Gray's Manual of Botany (8th edition).

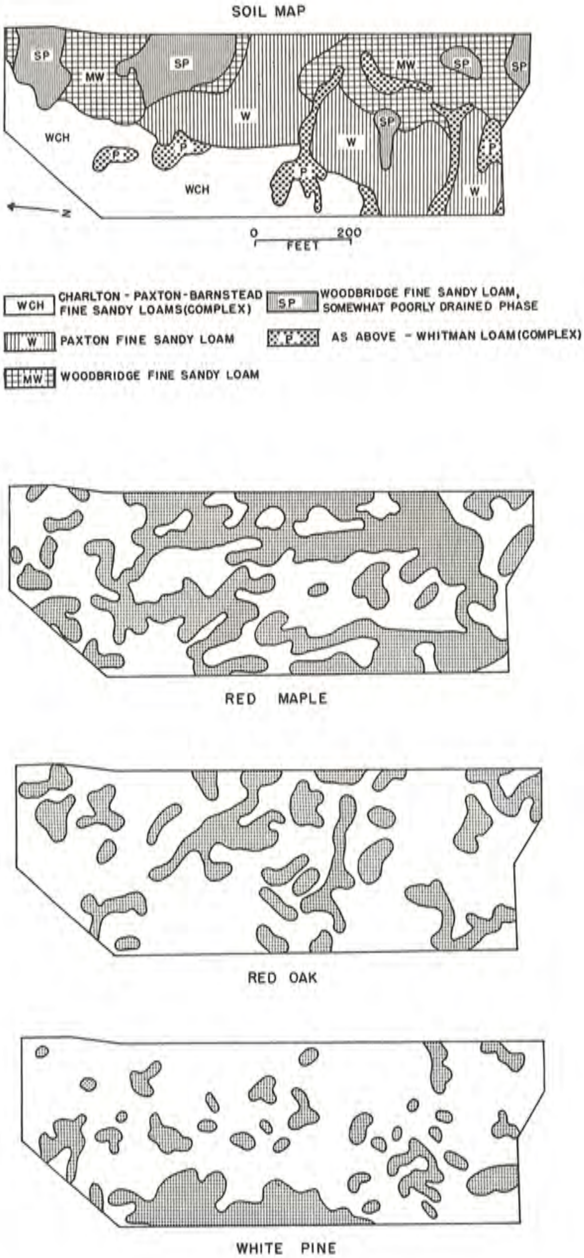


FIGURE 14. (Upper) Soil map of the 8 acre study area. (Lower three diagrams) Stand density maps showing distribution of red maple, red oak, and white pine in the forest canopy. Shaded areas show where the trees are less than 30 feet apart. Unshaded areas either have no trees or the trees are isolated and more than 30 feet apart.

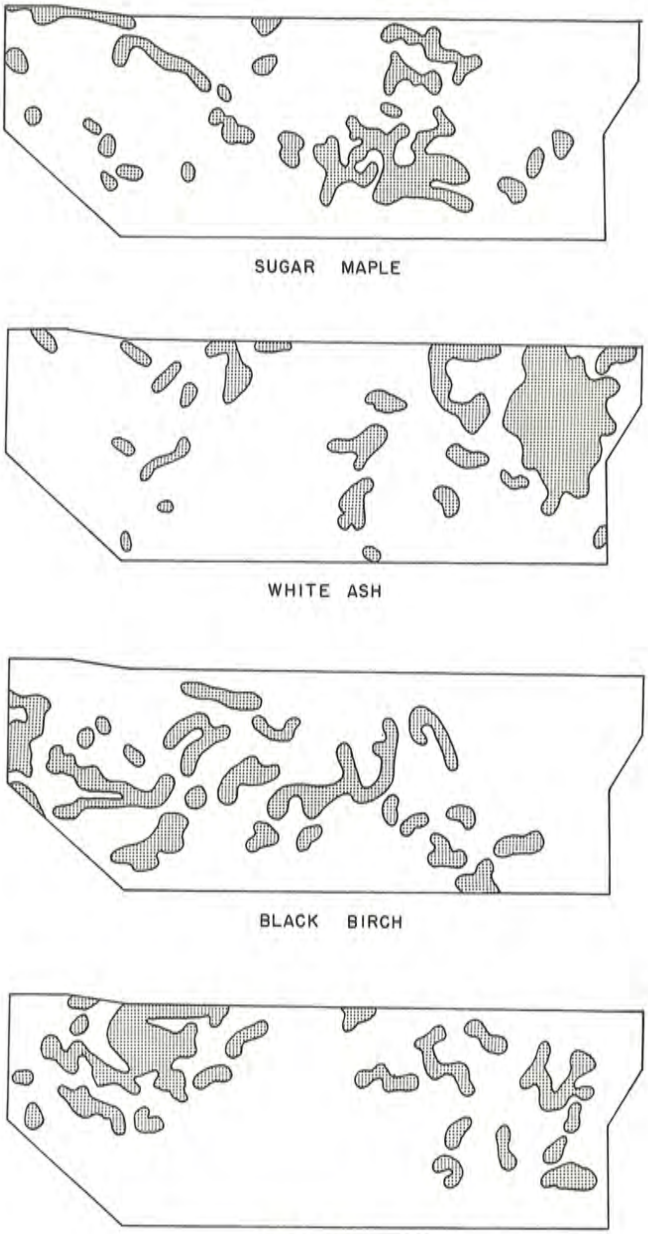


FIGURE 15. Stand density maps showing distribution of sugar maple, white ash, black birch, and paper birch in the forest canopy. Shaded areas show where the trees are less than 30 feet apart. Unshaded areas either have no trees or the trees are isolated and more than 30 feet apart.

FIGURE 16. Old growth stand in an area where red oak is predominant.

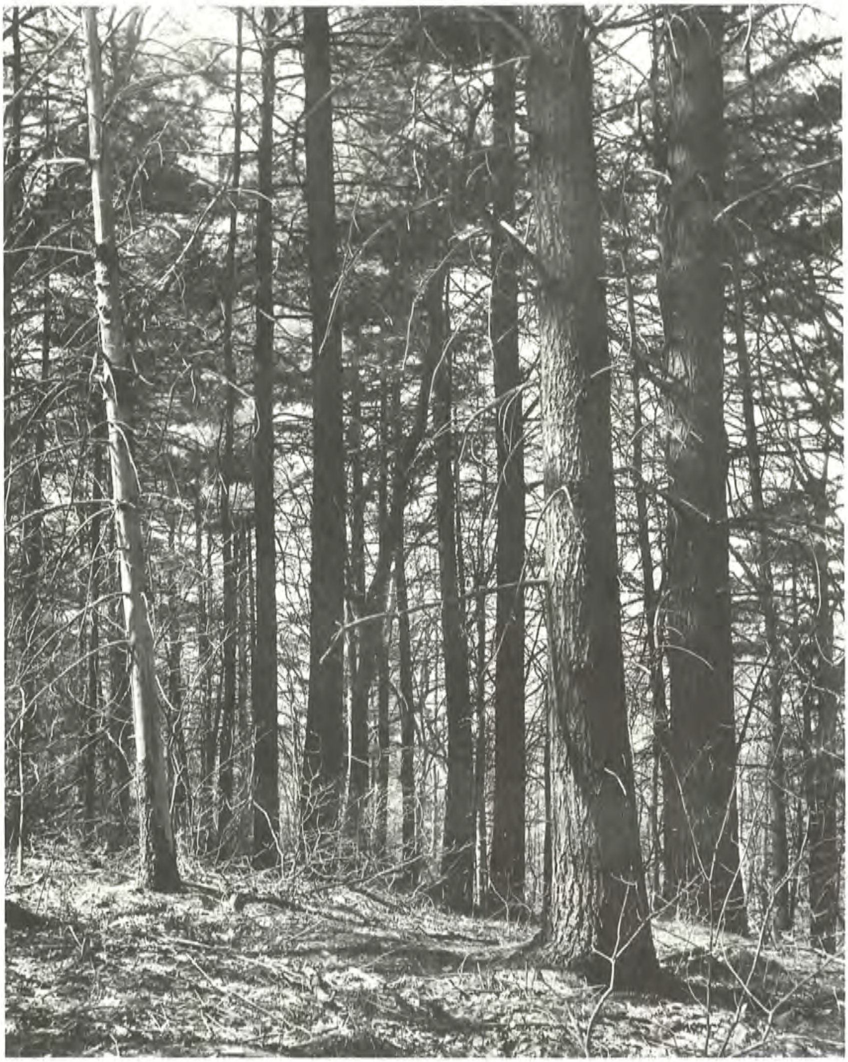


FIGURE 17. An almost pure white pine stand on the 8 acre tract.

and white ash trees are few. A comparison of Figures 14 and 15 shows that the distribution of sugar maple (193 stems) and the white pine tends to be mutually exclusive throughout the area, and that white ash (195 stems) and white pine show a similar but less pronounced tendency.

Black birch (205 stems), paper birch (197 stems), white ash, and sugar maple also grow in all parts of the area, but they are not uniformly distributed. Thus, black birch trees are rare in the southern end of the area near a small stream channel (Fig. 15), where paper birch (Fig. 18) and, particularly, white ash are abundant. Paper birch and white ash both form concentrations in the northern and southern parts of the area. Sugar maple trees are particularly abundant in the boulder concentration at the base of a short steep slope in the central part of the area.

Volume and basal area were measured in 1956 by E. M. Gould, Jr. and J. H. Patric. Each of Hatheway's soil pits served as the center for a relascope plot (Grosenbaugh, 1952). Figure 19 shows total volume in cubic feet per acre at each of 57 localities and the minimum number of species that comprise 50 percent of the volume in the upper crown class at each location.

The volume of wood recorded at the plots ranges from 700 to 4,100 cubic feet per acre, and the median volume is 2,000 cubic feet. The seven most abundant species make up most of the volume at all but 6 of the 57 plots. At the northeast corner of the area, hemlock comprises a large part of the volume at two points, as does basswood at two points in the southwest corner and hickory at two points in the southeast corner of the area.

The abundance of red maple stems is not reflected in volume of wood. Thus, red maple constitutes a large part of the volume at only 9 plots. Similarly, black birch, white ash, and sugar maple appear in the species lists at only 4, 5, and 2 points respectively. None of these four species, whose stems are abundant in the area, comprises as much as 50 percent of the volume at any plot by itself. Paper birch comprises 50 percent of the volume at 4 plots, in all of which the volumes are low — less than the median value for all 57 plots (Fig. 20).

White pine, red oak, or both contribute a large part of the volume in all but 10 of the plots. White pine alone comprises 50 percent of the volume in almost half of the plots in the two westernmost tiers. A large irregularly shaped block of 13 plots in which red oak comprises 50 percent of the volume extends across the middle part of the area.

Furthermore, the volume tends to be higher in plots in which red oak and white pine are listed. Figure 20 suggests that the highest volumes are dependent upon an abundance of white pine, rather than red oak.

However, plots in which red oak is listed also show high volumes, and only one plot in which neither red oak nor white pine is listed exceeds 2,000 cubic feet per acre.

Changes in the forest of the 8-acre area in the recent past

Changes in the forest since 1908 are documented in the files of the Harvard Forest and have been described by Spurr (1950). Prior to 1908, evidence of the nature of the forest from the time of settlement in 1733 depends largely upon the study of land-use history (Raup and Carlson, 1942), local histories (Whitney, 1793), and detailed reconstructions of forest history in adjacent parts of the Harvard Forest (Stephens, 1956). A general picture of the vegetation changes in the area since deglaciation is provided by studies of microfossils that are preserved in Tom Swamp (Davis, 1958).

At roughly 10-year intervals since 1908, the staff of the Harvard Forest has constructed stand maps. The stand map of 1908 indicates that the forest in the 8-acre area was old-growth hardwoods. The appearance of a "pine-hardwood" type in a stand map of 1926 probably reflects concern over the depletion of white pine in the whole area, rather than an actual increase of pine trees in the stand (Goodlett, 1960). In other words, patches of pine trees in hardwood stands might have been disregarded in 1908, when large blocks of mature pine trees were available for harvest.

A thinning or improvement cutting in part of the 8-acre tract was made in 1908–1909, in which about 3 cords and 3,000 board feet per acre of large-toothed aspen (poplar) was removed. In 1914–1915, 3,000 board feet of chestnut was cut, and after the hurricane of 1938 some white pine was salvaged along with 87 cords of fuelwood (Hatheway, 1954). The effects of these operations upon the forest are difficult to evaluate, but they do not constitute major cuttings.

In 1908, the age of the forest in the 8-acre averaged about 60 years. A few older trees were present. Presumably, most of the trees in the area were cut about 1850. Roughly the northern half of the area was woodland in 1850. The demand for wood at the time of the peak population from 1830 to 1860 probably was great. Hardwood stands, particularly those near the village, may have been cut over repeatedly for fuelwood, fence posts, and lumber. Few trees more than 4 inches in diameter would have remained after operations of this kind.

A map of the town of Petersham made in 1830 shows the 8-acre area as woodland (Raup and Carlson, 1942). The area, therefore, seems to have supported woodland since settlement.

Evidence on the ground, which has not been studied intensively, also

FIGURE 18. Paper birch concentration in the northern part of the 8 acre tract.

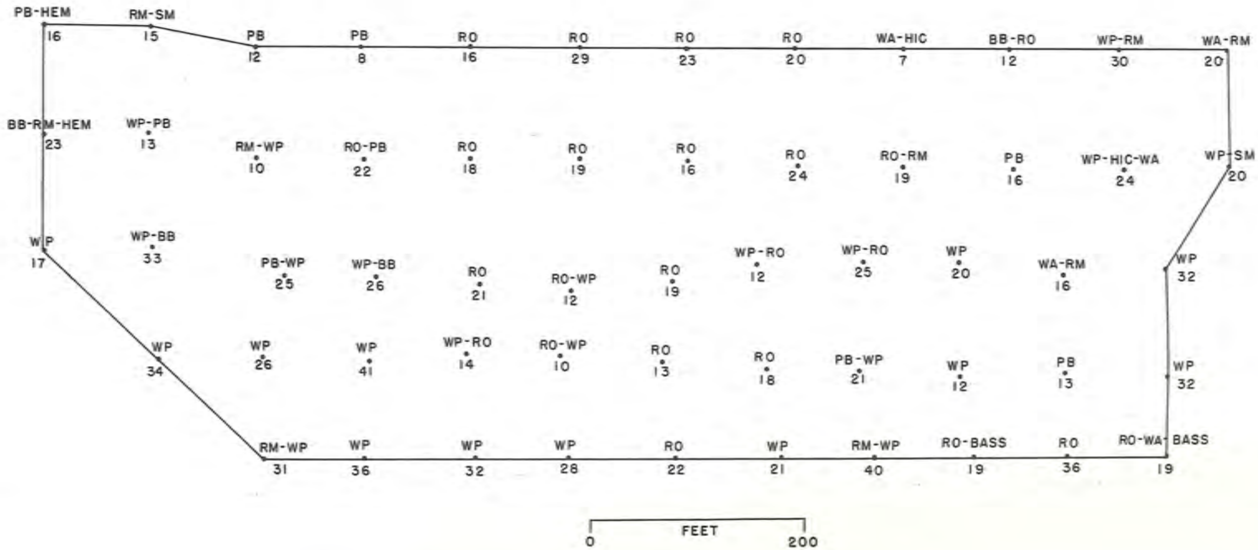


FIGURE 19. Species of trees that constitute 50 percent of the volume of the upper crown class, and the volume of all trees in the upper crown class at each of the relascope plots on the 8 acre study area.

BASS — Basswood
BB — Black birch
HEM — Hemlock
HIC — Hickory
RM — Red maple
RO — Red oak
PB — Paper birch
SM — Sugar maple
WA — White ash
WP — White pine

22 — Volume in hundreds of cubic feet per acre of all upper crown class trees at each relascope plot.

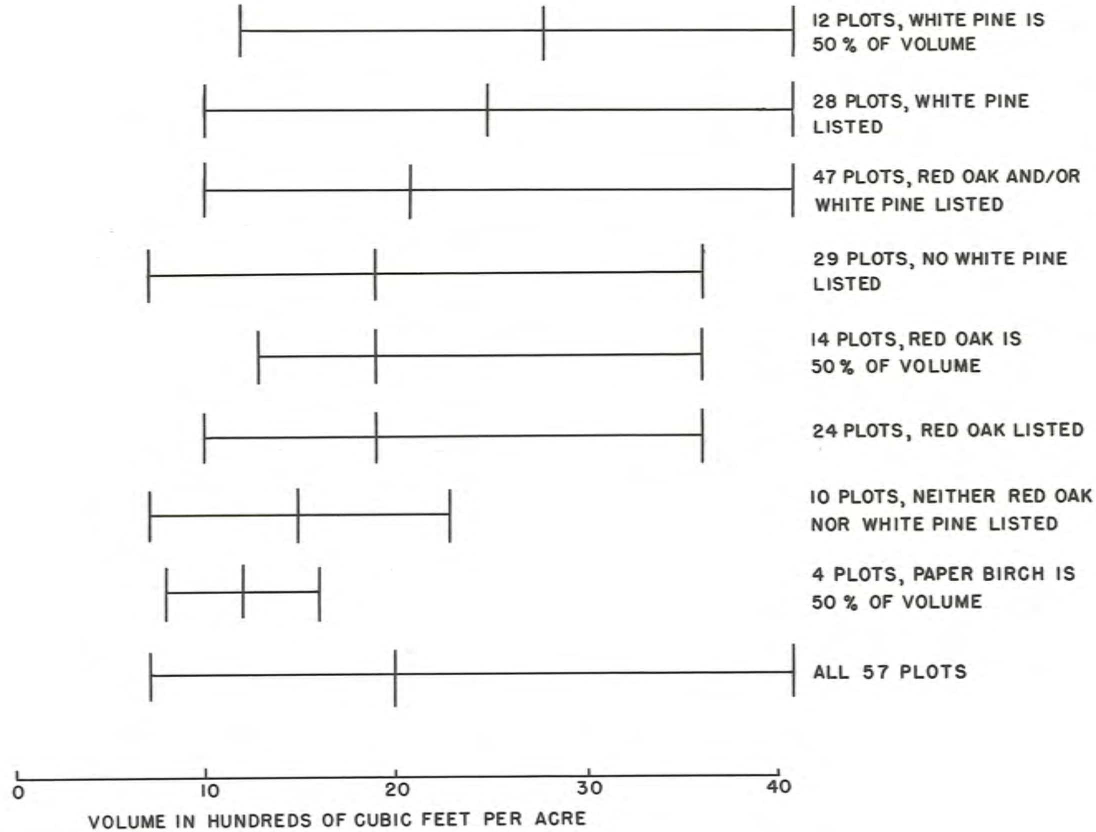


FIGURE 20. Relation between volume of wood and species composition at the relascope plots in terms of range and median values.

FIGURE 21. Stump illustrating a method of reconstructing the pre-settlement forest. The three chestnut sprout trees were cut in 1915 at about 65 years of age. The original tree is estimated to have been at least 125 years of age at the time of cutting so it was a seedling or young tree in 1733 when settlement took place.

indicates that the area has always remained in woodland. For example, a cluster of three chestnut stumps in the 8-acre area remains from the salvage operations of 1915 (Fig. 21). The arrangement of these stumps around a common base indicates their sprout origin from a large stump. At the time of cutting, the sprouts were 60–70 years old. Therefore, the stump from which they had a common origin is the remnant of a tree cut about 1850. If this much larger tree was only 100 to 125 years old when it was cut, a rather conservative guess, almost the entire span of time back to settlement in 1733 is represented by the stump complex.

Nevertheless, the composition of the forest in this 8-acre area from 1733 to 1850 is almost completely unknown. Studies in an old-growth hardwood forest in another part of the Tom Swamp Tract by Stephens (1955) indicate that the proportions of species have fluctuated rather widely as a result of cutting and wind damage, but that the kinds of trees remained essentially the same. Large fluctuations in the percentage of pine and hemlock result from the fact that these conifers do not sprout when cut, whereas hardwoods sprout vigorously. Therefore, pine and hemlock trees may have been more abundant in the past in the area. However, Peter Whitney's description of the vegetation of the uplands in Petersham, published in 1793, makes no mention of white pine in the area. Presumably, pine trees were no more conspicuous at that time than they are at present.

Relations between soils and forest in the 8-acre area

The soils and the forest were studied and mapped independently, but at the same scale, in order to test the hypothesis that differences in the soils are reflected in the vegetation. The range of variation in both soils and vegetation, however, is small. Almost the entire area is underlain by fragipan, and the areas lacking pans where sand and gravel reach the ground surface are too small to delineate individually at a scale of 66 feet to the inch. The soils range from somewhat excessively to poorly drained, but many of the areas are so small that the roots systems of individual trees probably grow in several different kinds of soil. The differences in the forest are even more subtle. Ninety percent of the stems in the forest canopy belong to seven species of trees, all of which grow in all parts of the area, although some of these species, as well as some of the less abundant species, tend to form concentrations. The comparison of forest and soils, therefore, is concerned with relations between soil differences of small magnitude and poorly-defined concentrations of various kinds of trees.

The fact that the area has been subjected to several operations and natural disasters since 1908 further complicates the comparative study. Chestnut was completely eliminated by 1915, poplar is too rare for analysis (1% of stems), and white pines are abundant now. The kinds of trees that replaced those cut, diseased, and wind-thrown stems have not been determined in detail. Many of the gaps in the canopy were filled by lateral expansion of crowns of adjacent trees, and other gaps appear to have been filled by red maples. More difficult to assess is the effect of the heavy cuts made in the area prior to 1908. In other words, the concentrations of species shown in the distribution maps may in large part be the result of cutting operations. Table 2 shows that all of the species that constitute as much as 10 percent of the total number of stems grow on all of the soil types that occupy as much as 8 percent of the area. This relation strongly suggests that the presence of concentrations of stems of a particular species is the result of factors other than differences in the soil.

The relations between species distribution and soils can be studied by superimposing the distribution maps of the various species and the soils map. This comparison is summarized in Table 2. White pine and white ash are the only species of the seven most abundant kinds of trees whose distribution appears related to the distribution of soil types. The remaining 12 species are too infrequent for this kind of analysis.

Hatheway (1954) listed all trees at each of the 57 soil pits whose crown was over the pit and whose diameter was more than one inch at breast height. He found that white pine grew at more of the driest stations than any other species. His ordination of moisture at the pits depended upon actual measurements of standing water in the pits from November 1951 to mid-June 1952. The moisture classes were further related to presence or absence of fragipan and depth to pan. The driest stations lacked fragipans, or the pan lay at distances of more than 35 inches from the ground surface. However, white pine was found at 27 of the stations, ranging from driest to wettest. Hatheway stated that the white pine might be of "old field" origin, but concluded on the basis of crown form and the sketchy knowledge of land-use history that the pines had "emerged successful in competition with the hardwoods."

The greatest concentration of white pine trees is on part of the Charlton-Paxton-Barnstead soil complex in the western part of the area. On this steep convex slope the sand and gravel deposits are mantled by thin aeolian and colluvial deposits. Pines are concentrated on most of the small areas where the fragipan is lacking and where sands and gravels extend to the ground surface.

Pure stands of white pine are common on sand and gravel deposits in central New England, and this relation has been established by many workers. White pine forms pure stands on these rather droughty soils not because of more rapid rates of growth but because the native hardwoods grow much slower. In other words, the relative growth rates of pines and hardwoods on the different kinds of glacial deposits differ markedly. Growth rates of both pines and hardwoods are greatest on till soils underlain by fragipans, but the formation of pure stands of pine on these sites depends upon elimination of hardwoods during the early years of the stand (Lutz and Cline, 1947; Goodlett, 1960). The most successful method of eliminating this hardwood competition has been through land clearing for cultivation or pasture and the complete removal of hardwood stumps. Heavy pasturing of cutover lands produces a similar result because the animals browse the hardwood seedlings and sprouts.

The establishment of a relation between the largest concentration of pines in the area and the glaciofluvial soils depends upon proof that the area was not cleared for cropland or heavily pastured. All of the available evidence indicates that the northern half of the 8-acre area was a woodlot from time of settlement, although it cannot be demonstrated that the woodlot never was grazed. If the stumps of pine trees blown down by the 1938 hurricane were included in the map of pine stems, the density of pine trees would be increased in several parts of the area. Nevertheless, the series of stand maps indicates that the concentration of white pines in the northern half of the area prior to the hurricane was centered upon the sand and gravel deposits, and not upon the till deposits. Furthermore, the distribution of pine stems in relation to soils (Table 2) shows a steady decrease in density as the soils increase in wetness.

White ash trees are most numerous in the canopy in the southern part of the 8-acre area, centered upon an area of moderately well- to poorly-drained soils. The largest concentration of white ash (Fig. 15) contains a small stream channel that drains the slope above the 8-acre area. Thus, this part of the study area stays wet for longer periods of time during the growing season than does the area of wet soils in the northern half of the study area.

White ash stems not only tend to be more abundant in areas of wetter soils (Table 2), but the only volume plots in which white ash is listed as an important species are found on soils mapped as moderately well or somewhat poorly drained. However, all areas of wetter soils do not support white ash trees, and white ash trees also grow on well- to somewhat excessively-drained soils, so the relationship to wet soils is not a close one.

Stout (1952) found that pure stands of white ash, in another part of Compartment I, invariably grew in places where the depth of the compact till layer, or fragipan, was 20 inches or less from the ground surface. Hatheway (1954) obtained essentially the same results in the 8-acre area, as did Patric (1956) in a larger area to the east in Compartment I. Patric further analyzed growth data that had been obtained at various times from sample plots established in Compartment I in 1933. His analysis showed that white ash regeneration was abundant in cutover pine stands, and that the ash grew rapidly for 15 to 20 years, after which time red oak trees tend to form most of the canopy. The initial abundance of ash seedling may be a function of the abundance of wind-borne ash fruits, or it may result from changes in soil moisture related to clear cutting (Holstener-Jorgensen, 1959; Trousdell and Hoover, 1955). The complete removal of pure stands of 60- to 70-year-old white pine trees may reduce loss of soil moisture through transpiration sufficiently to cause a temporary change in moisture regimes, increasing the chances of survival as well as the growth rates of white ash seedlings.

RELATIONS BETWEEN PRESENT FEATURES OF COMPARTMENT I AND PREHISTORIC EVENTS

Local deglaciation, which probably took place some 12,000 years ago, exposed a mantle of drift that provided the materials from which the present soils were derived. The nature of this drift, which consists predominantly of fine-grained, dense, platy till, presumably also determined the general configuration of the slopes. The subsequent modifications of the drift, as its surface form and its physical and chemical composition adjusted to a variety of processes, perhaps under a variety of climatic conditions and kinds of plant cover, cannot be traced in detail. However, some of the changes can be detected, and others need consideration even if they are highly speculative.

Subsequent to the deposition of the drift, gravity movement of the till formed a deposit of colluvium at the base of the slope. In the western part of the area, the colluvium overlies coarse sands and gravels, probably of glaciofluvial origin, and the boundary is abrupt. Gravity movement also is indicated by the distribution and orientation of boulders and the small landslide features.

The dating of these gravity movements is difficult. Some large boulders appear to have moved a few feet in the recent past. Nevertheless, no evidence of movement within the life of the oldest trees can be found, and soil development in the mounds of soil apparently pushed up by boulder movement suggests that movement took place more than 500 years ago. The chief movement of soil materials since occupation by colonists seems to have resulted from the formation and slow reduction of tree-throw mounds.

It is difficult to postulate the conditions prevailing at the time of these gravity movements. Deposits are rendered unstable on slopes of similar declivity at the present time by high moisture content and high runoff rates, as well as by the activity of ground frost. A lack of plant cover accentuates instability under these conditions. The smoothing of the slopes, the formation of the colluvium, and the formation of stone and boulder concentrations probably took place shortly after local deglaciation. At this time, the plant cover presumably was lacking or of tundra form (Davis, 1958). Lack of vegetation alone would increase frost activity, and the temperature regimes probably were severe. Soil moisture content probably was higher under this kind of plant cover, particularly if thick layers of ground frost persisted through much of the year or if permafrost was present. Deep thaw might lead to the formation of lobate terraces by mass movement of saturated materials over frozen layers.

A major difficulty in evaluating events lies in the fact that tree-throw has served to mix the upper 2 to 3 feet of the soil material, presumably ever since the area was occupied by forest. Thus, the search for soil features or patterned ground that characterize high altitudes and high altitudes where cold frost climates prevail at the present time has been unsuccessful. No stone polygons have been found in the study area, and the polygonal structure of the fragipan does not constitute reliable evidence of more severe temperature regimes.

Although Fitzpatrick (1956) believes that the polygonal structure in fragipans found in glaciated areas is related to permafrost, these features are found in all fragipans, and fragipans are found far south of the glaciated region.

The fragipan horizon seems to provide a valuable time marker. Its presence in the deposit of colluvium over sand and gravel indicates that it was formed after a period of gravity movement of materials, and that its existence is not dependent upon undisturbed till structure. Fragipans are present in the knolls and lobate terraces, and their upper surfaces roughly conform with the surface of the ground, which indicates that the pans were formed after the formation of these features. However, boulders as well as soil materials constituting small landslide features moved on the surfaces represented by the present fragipans. This suggests that these gravity movements took place after the formation of the fragipan. The upper surface of the fragipan does not conform to the surface form of the small landslide features, which may indicate that the time elapsed since the landsliding is too brief for pan formation or that the formation of fragipans depended upon conditions that differ from the present ones.

The hypothesis of fragipan formation presented previously does not require a cold frost climate, although deep freeze and thaw might be an agent in the loosening of dense till. The creation of cracks through alternate periods of wetting and drying, frost activity of no greater severity than at present, and the activity of tree roots enables the pedogenic processes to take place. The presence of fragipans in several different great soil groups suggests that fragipan formation may take place independently of pedogenic processes prevailing in the upper solum, or that it is perhaps preserved when once formed by some particular process. This means that the fragipan sequence of horizons could be considerably older than the upper sequence of horizons which presently exists. Once formed, the impermeability of a fragipan to water may serve to preserve it. However, the soils on the slip scars of the small landslides indicate that the fragipan is easily destroyed if exposed at the ground surface.

The rate at which Brown Podzolic soils can form from unmodified material has not been determined. On some sandy materials in the Cape Cod area, it is less than 4,000 years. Stephens' (1955) work on mounds suggests that the kind of material involved here, which includes a high proportion of B2 horizon material, tends to redevelop a weak profile in 400 to 500 years.

Since settlement, changes from hardwoods to white pine and back to hardwoods have not caused demonstrable changes in the kind or rate of soil development. It seems likely that overturned soils in tree mounds would be preserved to some degree, at least from the time the white man modified the forest so greatly; if at any time Podzols existed, remnants of the bleicherde or orterde would still persist. These have not been observed, but there is a good deal of evidence of buried Brown Podzolic B21 horizons.

SIGNIFICANCE OF LANDFORMS AND SOILS FOR FOREST MANAGEMENT

The dense, platy till covering the drumloidal hill upon which almost all of Compartment I is located, as well as the soils derived from it, produces a particular kind of substratum to which all plants that grow here must adjust. This environment is characterized by high water tables under present rainfall regimes, presumably a high content of oxygen in the ground water, and rather shallow rooting space. In theory, these characteristics lead to rapid growth of trees initially, followed by stagnation as root binding develops.

The thick mantle of till, concealing all bedrock, tends to produce essentially uniform environments from crest to valley floor, which are reflected in the general uniformity of the forest cover. A tendency for wetness and absence of deeply cut stream channels in the compartment contributes to the uniformity of habitats. The prevailing convexity of slopes is interrupted in the extreme northern part of the compartment by a small valley, and in the western part by a deposit of glaciofluvial sand and gravel, which forms a pronounced footslope. With these two exceptions, the variations in surface configuration are almost all produced by short steep slopes, small knolls, ridges, shallow waterways, and closed depressions. These minor relief features, some of which are almost certainly the result of landsliding, create minor variations in the environment. Distance from the ground surface to the upper surface of the fragipan is related to the minor relief features, as is the distribution of most of the stones and boulders.

The outstanding characteristic of the forest in the compartment is its remarkably uniform species composition, in spite of the fact that the use of the land varied widely in the past. Red oak, red maple, white ash, paper birch, and white pine trees form the canopy in old woodlots as well as in old fields that are further separated from the pre-settlement forest by one generation of white pines. Many of the trees in the old woodlots are sprout descendents of hardwoods that grew in the presettlement forest. None of the trees in the old fields that were cleared for cropland or permanent pasture is connected through sprout origin to the pre-settlement forest. All of the hardwoods in the old-field stands originated either as seedlings in the pure stands of white pine that followed abandonment of the farmland, as sprout descendents of these seedlings, or as another generation of seedlings that followed cleared cutting of the pines. Natural reforestation of the old fields and the subsequent cutover pine lands did not result in the appearance of species not found in the old woodlots, nor are the proportions of these species greatly different in the old fields and old woodlots. In other words, almost all of the compartment is mantled by transition hardwoods, both old woodlot and cutover pine lands, although other species combinations characterize the central hardwood type in other parts of the Harvard Forest. This close similarity between transition hardwood stands that are separated in time by many years of use as agricultural land and a generation of pine on one hand and those that remained continuously in woodlot on the other strongly suggests an adjustment between this kind of forest and this kind of habitat.

Within this area of transition hardwoods growing upon soils with fragipans, however, are variations in composition that are related to variations in the soils. The most pronounced differences in the forest involve concentrations of white pine and white ash trees.

The distribution of white ash concentrations seems clearly related to variations in depth to the fragipan horizon and resultant moisture in the soil. They are located in areas where the pan lies near the surface of the ground and the soils are wet. The single concentration of white pine trees in the study area is centered upon an area of glaciofluvial sands and gravels that lacks both the fragipan horizon and an overburden of fine-grained colluvium. The pine concentration does not occupy the entire area of exposed sand and gravel, but occupies a pronounced convexity. The combination of exposed sand and gravel and the convex surface presumably creates drier habitats to which pines adjust more successfully than hardwoods. Thus, the till soils of concave areas that contain fragipans near the ground surface and the sandy and gravelly soils lacking fragipans and fine-grained colluvium that mantle convex surfaces represent the rather narrow range of environmental extremes in the study area. The presence of these extremes of soil characteristics is reflected in the forest composition and, presumably, is the result of differences in moisture regimes.

The spacing of stones and boulders on the surface of the soil affects forest management operations, and perhaps stand density and the growth rates of the trees. Concentrations of large boulders restrict the use of heavy equipment, but in the narrow boulder fields of Compartment I the operations are not seriously impeded.

Concentrations of stones and boulders reduce the volume of soil in the zone of free-rooting and the total amount of stored water. These effects probably increase root competition, and may lead to growth stagnation in young stands. Stand density may be lowered, particularly in drier sites. However, direct effects of stones and boulders on the characteristics of the stands were not evaluated in the studies reported here.

Finally, in terms of the practical problem of the development of soil mapping criteria having maximum utility for forest management, the present study suggests that:

1. In small scale or reconnaissance mapping of soils in central Massachusetts, the presence of drumloidal form, boulders oriented normal to slopes, and forests of the transition hardwoods type might indicate areas underlain by fragipan. Conversely, presence of rock outcrops, forests of the central hardwoods type, and pure stands of white pine that contained old pine stumps might indicate areas where the soils lack fragipans.

2. In large scale or detailed mapping of soils, careful delineation of areas underlain by fragipans is necessary, but the mapping of variations in the depth to these pans is of much less value.

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